

DoD Center for Geosciences – Phase II

Executive Summary to the Final Report

under

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from the

**Cooperative Institute for Research in the Atmosphere
College of Engineering, Colorado State University
Fort Collins CO 80523**

to the

**U.S. Army Research Office
Research Triangle Park NC 27709-2211**

Prepared by: Participating Scientists *

Edited by: Thomas H. Vonder Haar, Principal Investigator

For the Period: September 30, 1994 - June 30, 1998

July 1999

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Introduction

This Executive Summary was written as a stand-alone volume that would give the reader a general overview of the purpose and outcomes of the Center for Geoscience Phase II. As such it does not contain any detail about the research or its process. If the reader is stimulated to know more about any particular line of research please refer to the three yearly reports. These reports and the referenced papers and journal articles contain full documentation for each research topic.

Task 1: Fog and Haze Observations – Kenneth Knapp, Ken Eis, Thomas Vonder Haar, Kirk Fuller

Original Intent (Goals) of the Research

The primary purpose was to investigate the ability to remotely sense battlefield visibility (light extinction). In doing so, 5 objectives were recognized:

1. Detection of aerosols over land using GOES-8 and NOAA-K/L/M,
2. Quantify the aerosol optical depth and relate to horizontal visibility,
3. Analyze microphysics of fog and aerosols / Estimate effects on battlefield operations,
4. Quantify limits of detectability of fog and haze from satellite information,
5. Explore lower limits of low visibility sensing from space.

Research Findings and Results

Objective 1 – Detection of aerosols over land using GOES-8 and NOAA-K/L/M

This objective is largely a part of the second objective, so the results of the optical depth retrievals are presented in the next section. It should be noted that no work was performed with data from NOAA-K, because it was not launched during Phase II due to many delays. All the aerosol retrievals were performed from GOES-8 imagery.

Objective 2 – Quantify the aerosol optical depth and relate to horizontal path extinction

The Interagency Monitoring of Protected Visual Environments (IMPROVE) aerosol monitoring sites were used as ground truths for satellite measurements. The IMPROVE sites measured aerosol extinction (which is inversely proportional to visibility) and scattering coefficients and aerosol chemical composition. GOES-8 data was collected at the CIRA ground station and used to investigate the aerosols over 4 IMPROVE sites in the Eastern U.S: Dolly Sods, West Virginia in the Monongahela National Forest (DOSO), Great Smoky Mountains National Park (GRSM), Mammoth Cave National Park (MACA) and Shenandoah National Park (SHEN). The aerosol optical depth was retrieved from the GOES-8 visible observations using an adding/doubling radiative transfer model, which required a priori assumptions on the aerosol size (defined by the parameter g) and composition (defined by the single scatter albedo, ω_o). The retrieved aerosol optical depth was then compared to the extinction (and scattering) measurements. Correlation coefficients of these comparisons are presented in Table 1-1 for 4 cases and 4 IMPROVE sites (cloud filtering effectively removed all the comparisons for case 2). Results show 8 significantly positively correlated comparisons.

In an attempt to further understand the uncertainties, the optical properties (ω_o and g) were estimated from IMPROVE and SEAVS data. During case 3 (July 1995) chemical data was

collected and analyzed at Great Smoky Mountain National Park (GRSM). The chemical compositions of the aerosol was determined by collecting aerosols for 3 days at a time. Table 1-2 shows side by side the correlation coefficients for comparisons at GRSM Case 3 using different days with and without a priori optical properties. The question arises when using chemical data from twice a week, how do the optical properties vary and how should they be applied to hourly τ retrievals. Comparing only three days (the days for which the chemical data was collected) shows large correlation, yet few data points (only 9). Yet, blindly using all days and applying the properties from the nearest day with chemical data decreases the correlation from 0.758 to 0.661. Therefore, there is a short span for which the optical properties derived from the chemical assays apply. Obviously, the chemical data increases the accuracy of the optical depth retrieval, however, higher temporal resolution chemical assay data is needed.

Table 1-1. Correlation coefficients for the comparison of τ retrieval to IMPROVE data without a priori information.

CASE	DOSO	GRSM	MACA	SHEN
1	0.223	0.870		0.993
3	-0.390	0.763	0.265	0.669
4		0.790	0.562	
5	0.722	0.139	0.0941	0.790

Table 1-2. Correlation of comparisons using *in situ* optical properties (g and ω_o) for specified Julian days.

Days in comparison	Chemical Data from Julian Day of 1995			r from chemical data	r from assumed g and ω_o
	193	196	200		
All days	191-194	195-198	199-200	0.661(31)	0.758(20)
3 days	193	196	200	0.801(9)	0.701(6)
4 days	193	195-196	200	0.858(12)	0.755(11)
6 days	193-194	195-197	200	0.875(21)	0.759(18)

Objective 3 – Analyze microphysics of fog and aerosols / Estimate effects on battlefield operations

Characteristics of aerosols, including microphysical, temporal and spatial, were studied in this research using *in situ* and remotely sensed data. Results show that τ varies differently in time from site to site. For instance, haze over Mammoth Caves National Park seems to persist more steadily than haze over Great Smoky Mountains National Park. Also, aerosols spatially vary more over land than over open ocean.

Objective 4 – Quantify limits of detectability of fog and haze from satellite instruments

The detectability of aerosols depends on the optical properties and the type of sensor being used. The aerosol's single scatter albedo and phase function determine how much radiance is reflected into the satellite field of view. Specifically, a situation can occur when an increase in aerosol optical depth does not affect the satellite detected radiance. This causes the aerosol to become undetectable and is known as the critical albedo. For instance, using ω_o and g as assumed in this study (0.965 and 0.75, respectively) the critical albedo occurs when the surface reflectance is 0.30. For the land surfaces studied here (dense forests, $\rho_{sfc} < 0.1$), the critical albedo was not of concern. However, the critical albedo can be significantly detrimental to aerosol investigations over brighter surfaces or of more absorbing aerosols.

Objective 5 – Explore limits of low visibility sensing from space

One of the results of the last two years of research is a fog product now being used by the National Weather Service's Western Region. We know the limits to our sensing method are as follows:

- Critical albedo – This phenomena produces non-unique solutions to the optical depth when the aerosol and surface reflectance are at certain known values. This phenomena can be worked around by using different wavelengths, waiting for the illuminating geometry to change, or using a different satellite's sensor for the affected location and time when critical albedo conditions are met.
- Signal-to-noise constraints – The GOES-8 visible sensor has trouble resolving optical depth features when the illumination is low (nighttime or local twilight)
- Quantization effects – The 10-bit pixel depth of the optical image gives a minimum sensitivity to optical depth measurements of 0.03.
- Surface reflectance changes – This is a major limitation. Rain-induced vegetation darkening or drying of land and vegetation cause the background to depart from the assumed background values used in the doubling and adding method.
- Long-term persistent aerosols – The doubling and adding technique assumes that a clear image is used to compare against the test image. All images contain some aerosol scattering.
- Aerosol chemistry – The doubling and adding method assumes a given aerosol optical property. The accuracy of that assumption is reflected in the optical depth output of the model's results.

Technology Transition

Aerosol total optical depth retrievals will be a candidate transfer topic during Phase III. The USAF is reviewing this topic for technology transition to AFWA as a prototype product in early 2000.

Students Supported

Kenneth Knapp, Atmospheric Science – Masters Completed

Published Papers

Knapp, K.R., 1996: Radiative effects of boundary layer aerosols: delectability of hazes by GOES-8 and estimation of their direct effect. Masters thesis, Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado, 112 p.

Knapp, K.R., K.E. Eis, T.H. Vonder Haar, and K.A. Fuller, 1996: Detection of battlefield visibility from satellite. Proceedings, 1996 Battlespace Atmospherics Conference, December 3-7, San Diego, CA.

Workshop Participation

July 16-18, 1997 DoD Center for Geosciences – Phase II Results Workshop
Pingree Park Mountain Campus, Colorado State University

July 29-31, 1998 Research Planning Retreat for the Center for Geosciences/Atmospheric Research, Pingree Park Mountain Campus, Colorado State University

Task 2: Fog Forecasting – William Cotton, J. Christopher Clarke

Original Intent (Goals) of the Research

Our original intent and goals were to combine the latest cloud physics, radiation, and soil vegetation surface energy budget models in RAMS to examine both the mesoscale and microscale structure of fogs.

Research Findings and Results

Simulations of the Po Valley Fog Experiment were performed. We focused on the fog event that began on 11 November during a special data period. Fog formed shortly after sunset on the 11th and continued, more or less continuously, over portions of the Po Valley until 14 November.

RAMS was set up in the following model configurations. To look at the larger scales involved in fog forecasting a mesoscale model consisting of two nested grids was used. The largest grid, Grid #1, used 80km grid spacing in the horizontal with vertical grid spacing logarithmically stretched from 100 to 2000 meters. The smaller grid, Grid #2, used 16km grid spacing, with the same vertical grid spacing as the first grid.

To look at small-scale effects, a high resolution, cloud resolving, two-dimensional model was used. These 2D model runs (or FRM for Fog Resolving Model) consisted of one grid, with 41 horizontal grid points, with grid spacing of 25m. Combined with the horizontal specification, the vertical grid was varied, with either 65, 75 or 130 grid points. Vertical grid spacing was stretched, with spacing varying from 1 meter to 200 meters.

For the mesoscale simulation, the model was initialized using data from 12Z NCEP upper-air data and surface observations. The model was integrated for 24 hours. In general, the model run was in reasonable agreement with synoptic scale observations over most of the model domain. However, very soon after initialization time, PBL winds in the Po Valley shifted from an observed westerly direction to an easterly direction. Upper-level winds were northeasterly over the mountains and the observed westerly winds in the valley were weak in strength and small in scale; the large-scale flow dominates the lower level, terrain generated flow. This shift in lower level flow had an impact on the location of fog formation compared to observations.

Determining why this Po Valley flow was poorly modeled was explored including: determination if valley circulations were forcing the lower-level westerly winds; and determination if soil moisture gradients were a factor. The results suggested that the circulation was not thermally-driven, which is aptly handled by this model configuration, but is dynamically-driven channel flow. Observations in the valley during this time also suggest that explanation.

Several 2D FRM runs have been done to explore the development and growth of radiation fog. Three runs have been completed, one corresponding to each of the microphysical parameterizations in RAMS. The model was initialized from sounding data taken from the Po Valley Fog case on November 11, 1989. The sounding was taken at 10am local time (+1 GMT). The model was integrated for twenty-four hours. The observations indicate that a fog forms soon after sunset, which lasted for the next three days.

Daytime temperatures are well predicted by each model simulation before fog forms. Boundary layer depths are also forecast well, with both the observed and modeled PBL heights around 450m. Each run produced fog on the date of the test case, November 11, 1989. The no-microphysics (NM) model and bin microphysics (BM) both produced fog at about the same time. The bin model produced fog slightly later in the evening. The NM model produced extremely high LWC since there is no "sink" of cloud water in this model. Both the bulk microphysics and BM produced less liquid water, with values of the bulk model being slightly higher and BM slightly lower than observed.

Fog forms initially as a shallow surface layer fog. As the evening continues, the fog begins to thicken and, after tapping the relatively high mixing ratios of the residual PBL, became a deep boundary-layer fog. This fog was optically thick and longwave radiational cooling occurred at fog top, leading to a well-mixed fog. However, the surface became shielded from significant longwave cooling. During this phase, relatively warm soil begins to heat the lowest layers of the surface layer, leading to unstable lowest layers of the fog. The eddies in this layer resemble afternoon convection, while the rest of the fog exhibits larger scale motions.

Technical Transition Activities

The fog simulation modules combined in RAMS in this research are now being implemented in a prototype real-time forecasting version of RAMS to examine the improvements to fog prediction they will yield.

Students Supported

J. Christopher Clarke, Atmospheric Science - Ph.D. work not yet completed

Published Papers

None to date.

Workshop Participation

July 16-18, 1997 DoD Center for Geosciences - Phase II Results Workshop
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July 29-31, 1998 Research Planning Retreat for the Center for Geosciences/Atmospheric
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Task 4: Cloud Drift Winds: New Development and Demonstration Systems – G. Garrett Campbell, James F.W. Purdom, Thomas H. Vonder Haar

Original Intent (Goals) of the Research

Improve the analysis of cloud motion by deriving geometric heights from multiple satellite views.

Research Findings and Results

A technique was developed which combines several satellite views to derive both motion and geometric height. This uses parallax information to derive height, but does *not* require *simultaneous* observations. The method proceeds through the following steps: collect a sequence of geosynchronous satellite images from one satellite. Re-map a satellite image from another satellite (either geosynchronous or polar) into the projection of the first satellite. Track objects in the time sequence with standard search for maximum correlation. Use the same search method in the remapped image to locate the same object. If a sequence of images is available from the second satellite, track the object in those as well. Take the set of locations, view points and observation times and prepare a least squares analysis to derive both motion and geometric height.

This was demonstrated for 1 km resolution visible data with height accuracies estimated at 0.5 km. Comparisons were made with shadow height estimates for verification.

The method has also been used with 4 km resolution IR data and 8 km water vapor data. These lower resolution data sets require the sub-pixel locations. That is derived from the array of correlations between images and yield repeatable locations to \pm 2 km. Case studies show matches between the heights and the visible and shadow heights.

Tests were performed with GOES West and GOES East, GOES East and AVHRR polar orbiter data and for a case with Meteosat data.

Further details are given at <http://www.cira.colostate.edu/GeoSci/windZ/windz.html>.

Technical Transition Activities

Technical transfers will be developed in the next phase of the Geosciences project. This theme has been transferred to EUMETSAT and will be transferred to AFWA in the next year as a prototype product for evaluation. Additionally NOAA NESDIS will be reviewing the method for possible use in the future. CSU continues discussions with ARL about possible inclusion of this research into IMETS and in support of artillery winds.

Students Supported

Capt. Mark Yeisley (AFIT), Atmospheric Science - Masters completed

Published Papers

Campbell, G.G., 1998: Practical satellite cloud height from shadows. *Mon. Wea. Rev.* (accepted)

Campbell, G.G., J.F.W. Purdom, C.E. Vaughn, 1995: Asynchronous stereo height and motion estimation from multiple satellite images. Proceedings, GOES-8 and Beyond, August 7-9, Denver, Colorado, SPIE Vol. 2812, p. 95-110.

Campbell, G.G., J.F.W. Purdom, C.E. Vaughn, 1996: Update on accurate cloud motions and heights using time adjusted stereo. Proceedings, Third International Wind Workshop, June 10-12, Ascona, Switzerland, EUMETSAT, p. 241-255.

Purdom, J.F.W., 1996: Detailed cloud motions from satellite imagery taken at one and three minute intervals. Proceedings, Third International Wind Workshop, June 10-12, Ascona, Switzerland, EUMETSAT, p. 137-146.

Yeisley, M.O., 1996: Low-level mesoscale wind field generation from cloud-track winds using GOES-8 imagery. Masters thesis, Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado, 81 pp. (Available as Atmospheric Science Paper No. 622.)

Workshop Participation

July 16-18, 1997 DoD Center for Geosciences - Phase II Results Workshop
Pingree Park Mountain Campus, Colorado State University

July 29-31, 1998 Research Planning Retreat for the Center for Geosciences/Atmospheric Research, Pingree Park Mountain Campus, Colorado State University

Task 5: Detection of Total Cloud Liquid Water (CLW) Over Land From a Combination of Microwave and Infrared Satellite Measurements – Thomas H. Vonder Haar, David Randel, Thomas Greenwald, Cynthia Combs, David Lawyer

Original Intent (Goals) of the Research

Investigate the potential of combining Special Sensor Microwave Imager (SSM/I) and infrared (IR) measurements to estimate cloud liquid water over land for use in meteorological applications. Specific goals: (1) test the accuracy/precision of the satellite retrievals through comparisons with ground-based microwave radiometer observations; (2) identify conditions under which the retrievals might be suspect; (3) develop new retrieval techniques; (4) explore possible applications.

Research Findings and Results

This work was also successful in identifying the strengths, weaknesses, and major sources of error in the CLW retrievals. For example, a single channel approach (85.5 GHz) is unable to detect low lying clouds, is highly susceptible to surface moisture effects caused by rain events, and is sensitive to the specified cloud top pressure (Greenwald et al. 1997b). Although this method has its weaknesses, it is able to capture the spatial variation of CLW (Greenwald et al. 1999).

The limitations in the single channel method led to the development of a new method based on the normalized polarization difference (NPD) at 85.5 GHz (Greenwald et al. 1996). The NPD method is relatively insensitive to the cloud height, surface skin temperature, and most surface moisture effects, which makes it robust and very attractive for general use. The retrieval skill is mainly determined by the degree of surface polarization, the uncertainty in the surface emissivity, and the amount of water vapor (Greenwald et al. 1999). The method should perform optimally in winter atmospheres over higher polarized land surfaces. In tropical environments, however, the increased amounts of water vapor and vegetation enhance the retrieval errors and likely make the method impractical. Based on surface emissivity statistics, this method is expected to be valid over a broad region of the U.S., excluding the southern Mississippi Valley where the surface polarization is negligible (Combs et al. 1998). An important secondary result of this study is that the effects of surface polarization seasonality were investigated for the first time. These data were extremely useful in characterizing the spatio-temporal variability of surface emissivity, which has a significant influence on the NPD retrieval errors.

Another important result involved the role of sub-FOV cloud effects in passive microwave retrievals of CLW from space. This is a concern because satellite measurements typically have coarse spatial resolution. It was found that broken cloudiness within the instrument's FOV results in systematic low biases in the retrievals, which is commonly called "beam-filling" (Greenwald et al. 1997a). These effects are expected to have a significant impact on the retrievals of CLW from current satellite-based systems.

Application of the SSM/I retrievals of CLW towards a method for operationally forecasting aircraft icing over land was encouraging for the limited number of cases studied (Lawyer 1996). However, additional regions and meteorological situations need to be studied to further refine and evaluate the satellite-based icing index. Preliminary comparisons of space borne microwave estimates of CLW over land to cloud top temperature indicated there is a rapid change in CLW near the temperature regime for conversion of water to ice. These limited results are promising and merit further investigation

Technical Transition Activities

Again the USAF, funded via the DMSP SPO is interested in this research and may possibly transition it to AFWA as a prototype product in the next 18 months.

The main thrust of this research is in its continuation into Phase III. It is a primary base for the start of the adjoint modeling effort now underway.

Students Supported

Capt. David Lawyer (AFIT), Atmospheric Science - Masters completed

Published Papers

Combs, C.L., T.J. Greenwald, D.L. Randel, A.S. Jones, and T.H. Vonder Haar, 1997: Satellite detection of cloud liquid water over land using polarization differences at 85.5 GHz. *Geophys. Res. Letters*, 25(1), 75-78.

Forsythe, J.M., D.L. Reinke, D.L. Randel, K.E. Eis, and C.L. Combs, 1996: CLVL: A global high-resolution layered-cloud database. Proceedings, 1996 Battlespace Atmospherics Conference, December 3-5, San Diego, CA.

Greenwald, T.J., 1998: Comments on "Comparisons of SSM/I liquid water paths with aircraft measurements. *J. Appl. Meteor.*, 37 655-656.

Greenwald, T.J., C.L. Combs, A.S. Jones, D.L. Randel, and T.H. Vonder Haar, 1996: A new method to estimate cloud liquid water over land using polarized microwave satellite measurements. Poster paper presented at the 5th Specialist Meeting on Microwave Radiometry and Remote Sensing of the Environment, November 4-6, Boston, MA (abstract in preprint volume).

Greenwald, T.J., S.A. Christopher, and J. Chou, 1997a: Cloud liquid water path comparisons from passive microwave and solar reflectance satellite measurements: Assessment of sub-field of view cloud effects in microwave retrievals. *J. Geophys. Res. - Climate and Atmos. Physics*, 102(D16), 19,585-19,596.

Greenwald, T.J., C. L. Combs, A.S. Jones, D.L. Randel, and T.H. Vonder Haar, 1997b: Further developments in estimating cloud liquid water over land using microwave and infrared measurements. *J. Appl. Meteor.*, 36(4), 389-405.

Greenwald, T.J., C. L. Combs, A.S. Jones, D.L. Randel, and T.H. Vonder Haar, 1999: Error estimates of space borne passive microwave retrievals of cloud liquid water over land. *IEEE Transactions on Geoscience and Remote Sensing*, 37, 796-804.

Greenwald, T.J., and A.S. Jones, 1998: Satellite observations of the ocean surface emissivity at 150 GHz. 1998 International Geoscience and Remote Sensing Symposium (IGARSS) '98, July 6-10, Seattle, WA.

Lawyer, David. T. 1995: Exploratory study of an icing index derived from satellite remote sensing over land. Masters thesis, Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado.

Workshop Participation

July 16-18, 1997 DoD Center for Geosciences - Phase II Results Workshop
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Task 6: Coupling of Satellite Remote Sensing of Land Surface Properties with a Hydrological Soil Model and Mesoscale Atmospheric Model – Andrew Jones, Ingrid Guch, Darcy (Noss) Molnar, Pierre Julien

Original Intent (Goals) of the Research

To understand the relationship of soil moisture and other related surface parameters with respect to information derived from satellite remote sensing in a coupled observational-modeling approach. Specific objectives: (1) to quantify the relationship of satellite remote sensing information to related surface parameters such as soil moisture, vegetation, and soil type; and (2) to develop a coupled model/satellite remote sensing approach to predict land surface parameters given specified surface forcing to the models from the satellite remote sensing data.

Research Findings and Results

A method for the coupling of the satellite infrared remote sensing data directly into an atmospheric mesoscale model has been developed and tested for several case studies. The surface soil wetness derived from the method has been corroborated with radar, surface precipitation stations, and microwave surface emittance measurements. The temporal variability of microwave surface emittance indicates a sensitivity to extreme surface flooding events, and shows feasibility of future DoD trafficability indices based on this fundamental microwave surface parameter (Jones and Vonder Haar 1996). For the quantitative coupled satellite-model work of Task 6, the GOES infrared heating rates were used in conjunction with the RAMS surface model. The method includes a prognostic soil model with explicit bare soil and vegetation surface components and was found to be successful at retrieving realistic spatial representations of the heterogeneous soil moisture (Jones et al. 1998a, 1998b). This method has shown promising results. A case study (one of several) was performed for 8 September 1991 over the Kansas/Oklahoma region, in which the microwave and precipitation data showed relatively high surface moisture gradient. The coupled satellite-model method was able to successfully retrieve wet conditions for the eastern portion and dry conditions for the western part of the region. This was corroborated by several independent data sources including the microwave surface emittance data (see Jones et al. 1998b). The work by Guch (1996) explored the atmospheric circulations which develop and interact with the surface wetness conditions retrieved from the coupled satellite-model method. In addition, several parameter sensitivity studies were also performed to determine strengths and weaknesses of the method.

The hydrological modeling work was substantially modified. The primary focus was on the Hickahala, MS watershed dataset of Task 7. Previously, we wanted to perform a larger scale case study over the Kansas/Oklahoma region using CASC2D in conjunction with the RAMS/GOES satellite data assimilation method, but soil moisture observations were limited for the data sets we had available. Due to time constraints and technical challenges, the single sensor NOAA soil wetness index (SWI) was used with CASC2D for soil moisture initialization over the Hickahala-Senatobia watershed with rather poor success. The NOAA SWI algorithm

appears to be an inconsistent indicator of surface wetness and did not perform as well as we had originally hoped, in that water vapor and cloud effects dominated the surface wetness signal. Future work should focus on the remotely sensed heating rates for quantitative data assimilation, or the possible exploitation of the atmospheric-corrected cloud-cleared microwave surface product of Jones and Vonder Haar (1997).

Technical Transition Activities

The primary transition activities of this task consisted of the various publications produced (please see the publication list below). Products developed under this task (such as the surface emissivity composites, and soil moisture retrievals) are slated for additional transition activities under Phase III. It is expected that the application of satellite-derived surface wetness estimates using the method developed under Task 6 will contribute to improved trafficability products. In addition, the Task 6 work provides a mechanism by which the surface boundary layer forcing in numerical weather prediction models can be driven by observed surface characteristics which are currently only poorly known.

The surface moisture product is also being transferred to ARL through scientific collaboration between Drs. Jones and Bleiweiss.

Future technical transition will also include comparison analysis of fog and thunderstorm forecasts initialized conventionally and with the soil moisture dry lines identified during this research.

Students Supported

Ingrid Guch, Atmospheric Science - Masters completed
Andrew Jones, Atmospheric Science - Ph.D. completed

Published Papers

Eis, K.E., and A.S. Jones, 1997: A fused method of determining soil moisture using high resolution geostationary imagery. Preprints, Cloud Impacts on DoD Operations and Systems, 1997 CIDOS Conference, September 23-25, Newport, RI.

Guch, I.C., 1996: The use of a satellite-model coupled system to study soil moisture effects on mesoscale circulations. Masters thesis, Department of Atmospheric Science, Colorado State University, Fort Collins, CO, 102 pp.

Jones, A.S., 1996: The use of satellite-derived heterogeneous surface soil moisture for numerical weather prediction. Ph.D. dissertation, Department of Atmospheric Science, Colorado State University, Fort Collins, CO, 522 pp. [also ATS Paper No. 617].

Jones, A.S., and T.H. Vonder Haar, 1995: Microwave surface emittance retrieval using coincident microwave and infrared satellite data. Preprints, *International Geoscience and Remote Sensing Symposium, (IGARSS) '95*, 10-14 July, Florence, Italy, 754-756 (invited paper).

Jones, A.S., K.E. Eis, and T.H. Vonder Haar, 1995: A method for multisensor-multispectral satellite data fusion. *J. Atmos. and Oceanic Technol.*, **12**, 739-754.

Jones, A.S., I.C. Guch, and T.H. Vonder Haar, 1996: Data assimilation of GOES diurnal heating rates as proxy surface wetness data into a regional atmospheric mesoscale model. Preprints, 11th Conference on Numerical Weather Prediction, August 19-23, Norfolk, VA, p. 125-127. Amer. Meteor. Soc.

Jones, A.S., and T.H. Vonder Haar, 1997: Retrieval of microwave surface emittance over land using coincident microwave and infrared satellite measurements. *J. Geophys. Res.*, **102**, 13609-13626.

Jones, A.S., I.C. Guch, and T.H. Vonder Haar, 1998a: Data assimilation of satellite diurnal heating rates as proxy surface wetness data into a regional atmospheric mesoscale model, Part I: Methodology. *Mon. Wea. Rev.*, **126**, 634-645.

Jones, A.S., I.C. Guch, and T.H. Vonder Haar, 1998b: Data assimilation of satellite diurnal heating rates as proxy surface wetness data into a regional atmospheric mesoscale model, Part II: A case study. *Mon. Wea. Rev.*, **126**, 646-667.

Washburne, J., and A.S. Jones, 1998: GLOBE soil moisture and temperature used to validate SSM/I-derived soil moisture and GOES-derived surface heating rates - Preliminary results. AGU Spring Meeting, Boston, MA (poster session).

Workshop Participation

January 19, 1995 Workshop on Two-Dimensional Surface Runoff Modeling
 Main Campus, Colorado State University
 Fort Collins, Colorado

July 16-18, 1997 DoD Center for Geosciences - Phase II Results Workshop
 Pingree Park Mountain Campus, Colorado State University

July 29-31, 1998 Research Planning Retreat for the Center for Geosciences/Atmospheric Research, Pingree Park Mountain Campus, Colorado State University

Task 7: 2-D Hydrological Modeling of Mesoscale Convective Systems – Pierre Julien, Darcy K. Molnár, Amit Sharma, Andrew Jones

Original Intent (Goals) of the Research

This task was directed to extend previous hydrologic modeling using the two-dimensional distributed model CASC2D (developed at Colorado State University under Phase I of the Center for Geosciences) to the mesoscale. Verification of that the model at the mesoscale level is a primary goal of this work. One of the major technical issues is the optimum grid size determination given the spatial variability of the terrain and spatial-temporal characteristics of thunderstorms.

Research Findings and Results

The model was successfully applied at the mesoscale on the Hickahala-Senotobia Watershed in Mississippi. A method has also been developed to determine the optimum grid size given the spatial variability of the terrain and spatio-temporal characteristics of thunderstorms. The research program for D.K. Molnár focused on the applicability of surface runoff models at larger grid sizes. The effects of grid size on surface runoff calculations were examined using the two-dimensional distributed model CASC2D developed at Colorado State University under Phase I of the Center for Geosciences. She examined the grid size effects on a small watershed to extend the analysis to larger watersheds. So far, two watersheds of interest to Army Laboratories have been used: Goodwin Creek, 21 km², and Hickahala, 540 km², both located in Northern Mississippi. The data sets for both watersheds are readily available in GRASS GIS format and the Goodwin Creek data has been used for surface runoff calculations with our two-dimensional hydrologic model CASC2D. Simulation results are available for both watersheds at grid-sizes varying from 30 m to 1 km.

Amit Sharma is working on subsurface flow with the intent to quantify the conditions under which subsurface flow may become important in calculating outflow hydrographs from watersheds. The important contribution is to calculate time-varying two-dimensional subsurface flow on each pixel and determine the rate of subsurface flow feed back into the channel network. In order to achieve this, water that infiltrates into the soil is routed as subsurface flow and resurfaces into the channels. The physical problem was formulated, and algorithms for subsurface flow were coded and tested on both a small test plot and the Goodwin Creek watershed. The model was tested with field data. The model performs appropriately on small scale plots and water mass balance has been tested within 0.01% of the total mass of water. Testing on highly instrumented watersheds is essentially complete.

Since the Center for Geosciences Workshop on Two-Dimensional Surface Runoff Modeling on January 19, 1995, significant advances have taken place through our hydrologic modeling effort on the following aspects:

- 1) The challenge of performing surface runoff calculations on large watersheds (exceeding 100 km²) is indeed daunting but we have been capable to perform calculations with half-a-million pixels to describe large watersheds.
- 2) We have developed the capability to calculate the relative proportion of two mechanisms generating surface runoff in Horton (rainfall excess) versus Dunne (saturation excess). Since sub-surface flow contributions are increasingly important in large watersheds, it has been concluded to devote some effort to it.
- 3) We maintained a continuous exchange of ideas with Army Laboratory scientists. Billy E. Johnson, Jeff Jorgeson, Bill Martin, Mark Jordan and Nolan Raphelt from the Waterways Experiment Station welcome direct interaction and use of the model CASC2D on some watersheds of interest to WES. Billy E. Johnson spent a full year of long-term training with us and completed his Ph.D. degree in May 1997. His interests centered on field applications of the model CASC2D to the Yazoo river basin under the Demonstration Erosion Control (DEC) Project. Jeff Jorgeson received WES approval for long-term training toward a Ph.D. in Civil Engineering and he spent one year at Colorado State University in the Hydraulics Program. He has completed his course work and passed both the qualifying exam and preliminary exam.

A total of 8 refereed journal publications and 3 conference papers have been published since 1994.

Technical Transition Activities

A Center for Geosciences Workshop on Two-Dimensional Surface Runoff Modeling was held at CSU on January 19, 1995. The morning sessions included in-depth discussions of spatial and temporal variability in hydrology, and the afternoon sessions focused on the intricacies (nuts-and-bolts type) of numerical modeling. The workshop fostered an exchange of ideas with Army Laboratory scientists. Bill Johnson, Jeff Jorgeson, Chuck Downer, and Nolan Raphelt from the Waterways Experiment Station joined us. We used this opportunity for direct interaction and use of the model CASC2D on some watersheds of interest to WES.

A tentative plan for future research includes support for fundamental research on:

- 1) erosion and sediment transport; 2) integrated hydro-climatic analysis of extreme events; and
- 3) flood forecasting.

- 1) Sediment Transport Modeling. There are significant problems caused by surface erosion in Army training areas, as well as sediment transport in streams monitored by the US Army Corps of Engineers. Surface erosion, bank erosion and sediment transport could be linked to the existing model CASC2D for dynamic simulations of sediment transport during major storms. Fundamental research is needed to develop and test the algorithms with terrain data. For the first time, a model that simulates the dynamics of sediment transport could be developed. This achievement would be possible because of the unique two-dimensional nature of the dynamic simulations of surface runoff from CASC2D. Fundamental research at the Center for

Geosciences at Colorado State University could lead to the successful development of powerful algorithms and offer new potential applications at Army training sites such as Pinon Canon, as well as the Demonstration Erosion Control area in the Yazoo river basin.

2) Mesoscale Hydrologic Modeling of Extreme Events. Extreme hydrologic events can have devastating consequences on military infrastructures and the battlefield environment. There is an inherent increase and decay in flood magnitude versus drainage area that needs to be defined to protect infrastructures against devastating flash floods. Fundamental research is required to determine the effects of topography and orographic precipitation on extreme surface runoff events. Fundamental questions to be addressed include: a) what is the effect of topography on the distribution of rainfall precipitation during extreme events; and b) what is the expected magnitude and frequency of devastating runoff events at various locations on a highly varied watershed. This would require full integration with climatological data and use of radar and satellite-based remotely-sensed rainfall precipitation. There is sufficient information to calibrate a hydrologic model like CASC2D for extreme events. Basic research at the Colorado State University Center for Geosciences could yield new technology and provide fundamental answers to prevent or forecast life threatening events like the devastating Big Thompson flood in 1976 that claimed 140 lives. These new research results would then be used in the battlefield environment.

3) Military Flood Forecasting. The recent experience with the Sava River flood in Bosnia clearly indicated how vulnerable military operations can be without appropriate flood forecasting technology. The model CASC2D developed at Colorado State University under Phase I of the Center for Geosciences offers the real potential for the integration of rainfall, topography, soil types and land use in order to calculate overland flow and surface runoff in channels from large watersheds. fundamental research is required to define water levels and flow velocities at particular river crossing sites during major flood events. Fundamental questions are given that the river is at a certain stage and that it rains on the watershed at a certain rate at certain locations, what is the water level and flow velocity going to be 12 h, 24 h, and 48 h from now? The proposed research would seek answers through the application of the CASC2D model with remotely sensed data and with the development of enhanced routines to determine the channel conditions in terms of cross-sectional geometry, roughness and river morphology. The results would provide advanced technology that could eventually be used for the prediction of flood conditions prior to military operations.

Students Supported

Jeff Jorgeson (Army Corps. of Engineers/WES), Civil Engineering – Ph.D. in progress
Billy E. Johnson (Army Corps. of Engineers/WES), Civil Engineering – Ph.D. completed
Darcy K. Molnár, Civil Engineering – Ph.D. completed
Amit Sharma, Civil Engineering – Ph.D. completed

Published Papers

Doe III, W., B. Saghafian, and P.Y. Julien, 1996: Land-use impact on watershed response: the integration of two-dimensional hydrologic modeling and GIS. *Hydrological Processes J.*, (10), 1503-1511.

Julien, P. Y., 1996: Transforms for runoff and sediment transport. *J. Hydro. Eng., ASCE*, 1(3), 114-122.

Noss, D. K., and P. Y. Julien, 1996: Calculating upland erosion using GIS-GRASS. *Proceedings, AGU 16th Annual Hydrology Days* (April 15-18), Colorado State University, Fort Collins, CO, 371-382.

Saghafian, B. and P.Y. Julien, 1995: Time to equilibrium for spatially variable watersheds. *J. Hydrology*, 172, 231-245.

Workshop Participation

January 19, 1995 Workshop on Two-Dimensional Surface Runoff Modeling
Main Campus, Colorado State University
Fort Collins, Colorado

July 16-18, 1997 DoD Center for Geosciences - Phase II Results Workshop
Pingree Park Mountain Campus, Colorado State University

July 29-31, 1998 Research Planning Retreat for the Center for Geosciences/Atmospheric Research, Pingree Park Mountain Campus, Colorado State University

Task 8: A Multisensor Approach to the Remote Sensing of Water Vapor – Christopher Lietzke, Franklin Evans*, Merritt Deeter*, Thomas Vonder Haar, Graeme Stephens

Original Intent (Goals) of the Research

By the early 1990's the DMSP had flown several "Special Sensor" instruments to attempt to obtain vertical profiles of water vapor and temperature over remote and/or data-denied regions. The need to detect the location of jet streams, weather fronts, developing severe weather and changing density profiles in battlespace areas and along ferry routes was obvious. Remote sensing technology was promising yet useable operational products were not reaching the USAF and Navy Forecast Centers. Tactical terminals for Army and other support were also not receiving necessary products related to water vapor and temperature conditions aloft.

At the DOD Center for Geosciences we proposed a rather radical new approach. Our objectives for this research task were to combine the best of the infrared and microwave sensors with a new, hybrid profile retrieval technique into a new method suitable for operational use in complex weather conditions.

Research Findings and Results

Remote sensing of water vapor through cloudy conditions is the most challenging atmospheric profile to obtain from satellites (or from the ground). We attacked that problem with a new Bayesian (conditional probability) method and the 183GHZ radiances from the SSM/T2 instrument first flown on DMSP in the early 1990's. We added infrared radiance data, and an IR model, to the system and tested our results for both clear and cloudy sky conditions using coincident satellite and rawinsonde observations.

After more than 2 years of research and testing our new approach provided very good results (Figure 8-1). The left side of the figure shows that a "reduced" set of 13 (4 clear, 9 cloudy) cases provides results with RMS error of less than 20%. Relative Humidity in comparison to ground -launched rawinsondes (considered "truth" for this test). On the right the microwave-only "reduced" (most time coincident) 13 cases had little or no bias. All cases compared provided results better than using a climatological mean profile which is often the only information available in data-denied areas

* Part of the work under this task was conducted via a subcontract with Dr. K. Franklin Evans, Program in Atmospheric and Oceanic Sciences, at the University of Colorado. The contract period was 10/1/94 - 9/30/97.

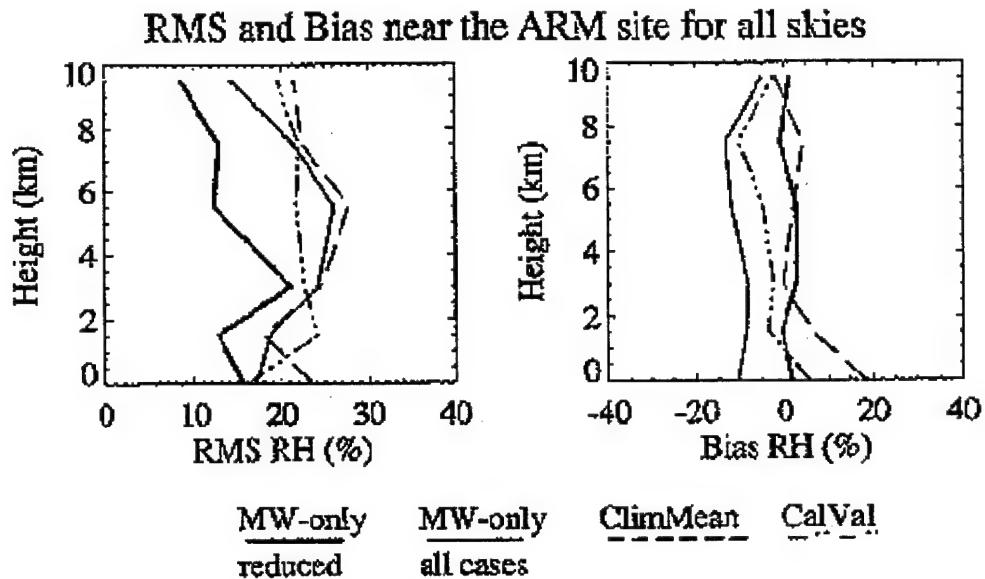


Figure 8-1

Several papers have been presented and one Ph.D. student used the new Bayesian Water Vapor Retrieval (BWR) method as the principal tool in a study of 3-D water vapor conditions in the Eastern Tropical Pacific. Other research groups are presently using the method on both DMSP SSM/T2 and NOAA AMSU-B data.

Technical Transition Activities

We are combining the new water vapor profiles with temperature profiles to support both Battlespace Weather Forecast Models and the artillery system of today's Army. Much of this tech transfer as well as the refinement of the research methods and tests will be the subject of the next phase of the DOD Center for Geosciences research under the Battlespace Weather research theme area.

A sub-task of our research involved use of a new Radiative Transfer Method to study the effects of ice clouds on the SSM/T2 retrievals. We developed the new code and provided it to DOD and civilian users via the web.

Students Supported

Christopher Lietzke, Atmospheric Science – Ph.D. completed
 Merritt Deeter, University of Colorado – M.S. completed

Published Papers

Deeter, M.N., and K.F. Evans, 1998: A hybrid Eddington-single scattering radiative transfer model for computing radiances from thermally emitting atmospheres. *J. Quant. Spectr. Radiat. Transfer*, 60, 635-648.

Lietzke, C.E., 1998: Satellite moisture profiling of the tropical eastern Pacific convergence zone. Ph.D. dissertation, Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado, 126 p. (available as Atmospheric Science Paper No. 646).

Lietzke, C.E., K.F. Evans, and T.H. Vonder Haar, 1996: An algorithm for water vapor profile retrieval from GOES-8, SSM/T-2, and SSM/I satellite data. Preprints, 8th Conference on Satellite Meteorology, January 28-February 2, Atlanta, GA (AMS).

Lietzke, C.E., and T.H. Vonder Haar, 1997: Regional water vapor transport in the North Atlantic Basin. Preprints, 13th Conference on Hydrology, February 2-7, Long Beach, CA (AMS).

Workshop Participation

July 16-18, 1997 DoD Center for Geosciences - Phase II Results Workshop
Pingree Park Mountain Campus, Colorado State University

July 29-31, 1998 Research Planning Retreat for the Center for Geosciences/Atmospheric Research, Pingree Park Mountain Campus, Colorado State University

Task 9: High Spectral Resolution Lidar (HSRL) Technique for Assessing Aerosol, Wind, and Temperature Variability – Joe She, David Krueger, John Hair

Original Intent (Goals) of the Research

The objective of Center for Geosciences Phase II Task 9 was to develop a prototype Rayleigh-Mie Lidar for measuring aerosol, line-of-sight wind, and temperature, and to assess the variability of such measurements.

Research Findings and Results

The ability to measure all these atmospheric parameters with a single Lidar is unique. This is possible only when a receiving molecular resonance notch filter and a stable narrow band transmitter are employed. Due to a delay in receiving the seed laser, we decided to pursue only aerosol and the more demanding temperature measurements, and to postpone field wind measurements. A simulation feasibility study for wind measurement with this type of Lidar system was however performed (Liu et al., 1996a, 1996b). Second, to enhance measurement accuracy, additional field measurements on aerosol and temperature at both 589 nm and 532 nm were planned and carried out, occasionally with simultaneous balloon sounding.

Overall, with efforts continued after the funding period, the progress to date suggests that all sub tasks have been investigated and carried to a satisfactory conclusion, indicating that the proposed Lidar indeed is capable of simultaneous measurements of aerosol (aerosol extinction and backscattering coefficient) and state (density, pressure and temperature) parameters of the atmosphere. With a modest system (a 5 W laser and a 8 inch telescope), these parameters have been determined to within useful precision in a 1 hr integration time up to a 15 km range. Unexpected problems associated with spectral purity in the laser transmitter at 532 nm and continuum state absorption in the iodine filter have been identified. Suggestions to improve the Lidar to reduce these problems have been studied; they should be experimentally investigated and implemented with associated engineering if the prototype Lidar that we developed is to become robust enough for routine atmospheric monitoring and measurements.

Interim Lidar System at 589 nm and Field Results

Initial temperature profiles measured at 589 nm show an unknown "wave structure" within 1s error bars ranging from ~ 3 K at 1 km to ~10 K at 5 km (Caldwell et al., 1996). After further experimentation and data analysis, we have concluded that most of the uncertainty is due to photon noise, which is the result of the low linear count rates possible with the photo multipliers (PMT) used. We had to reduce the laser power from an available 500 mW at 589 nm to ~25 mW to prevent photon pile-up in the received signal.

Presented in Figures 9-1a and 9-2 are the concluding field results with the 589 nm system, performed on June 3, 1996, along with a balloon measurement at the same site. In

Figure 9-1a, the measured temperature profile, which has considerable uncertainty, is plotted with the balloon sounding. The trend of the Lidar profile agrees well with the balloon sounding without any systematic bias, and the "wave pattern" can be seen clearly. For comparison, a calculated temperature profile that uses simulated data that matches the balloon sounding temperatures with random photon noise corresponding to Lidar signal levels added. A typical calculated profile, which only contains photon noise errors, shows a "wave pattern" of comparable spatial frequencies and amplitudes but with somewhat different phases, suggesting that photon noise is to blame.

For comparison, we studied a system operated at 532 nm, using PMT's that are 10 times faster to minimize photon pile-ups and a dual beam transmitter (250 mW of average power transmitted coaxial to the telescope and 1 W biaxial 20 cm from the telescope axis) to reduce the dynamic range of the signal levels received. A calculated profile for the same balloon sounding in Fig. 9-1a with signal strength (and associated photon noise) of the system is shown in Fig. 9-1b, having much reduced measurement uncertainty, 0.5 K at 1 km and 1.5 K at 4 km, with the same integration time (42 minute).

That our Lidar is capable of probing aerosol properties can be demonstrated by reviewing the simultaneously measured (June 3, 1996) backscatter ratio profile and total extinction profile, respectively on the left and right of Figure 9-2. Although long time average is needed to obtain good signal to noise due to slow PMT used at 589 nm, the profiles look very good.

Lidar System at 532 nm and Field Results

In the Spring of 1997, a new Lidar system at 532 nm was in operation. Since the Lidar system uses the spectral information from the scattered returns and must be capable of tuning to the center of an iodine absorption, the laser transmitter must have high spectral resolution (\sim 100 MHz) and be tunable over \sim 10 GHz. As shown in Figure 9-3, a Lightwave model 142 cw dual wavelength laser having 50 mW of both 1064 nm and 532 nm light is used. The 1064 nm light is used to seed a pulsed doubled YAG laser from Spectra Physics model DCR-3D producing tunable and Fourier transform limited transmitting laser pulses. The cw 532 nm light is frequency locked to provide an absolute frequency reference using iodine Doppler-free saturated absorption spectroscopy, with an active feedback control loop.

The detection system uses a relatively small 8-inch Cassegrain telescope. A Daystar filter with a FWHM of 130 GHz has been installed in the receiving system to eliminate rotational and vibrational Raman scattered light from the return signal, eliminating the need to include them in data analysis. In addition, this also allows measurements to be made near dusk and dawn. The signal is then split into three channels. Two molecular scattering channels have iodine vapor filters, while an un-filtered channel measures the total Rayleigh-Mie scattering as shown in Figure 9-3.

While continued improvements on Lidar at 532 nm are being made, field measurements have been made in several nights. The data taken on the night of May 4, 1997 demonstrated reduction of photon pile-ups giving a hourly average temperature profile with \sim 6.5 K/km lapse

rate up between 2 and 10 km with good signal-to-noise. There exists a systematic temperature bias (somewhat varied at different times) in these runs, attributable mainly to poor laser spectral purity. After subtle laser re-alignment and costly repair, field data were taken on September 6, 1997. Measurements this night with improved laser stability then revealed the need to maintain high stability of iodine filter and to avoid opening the housing between filter function measurement and data acquisition. This night with interesting cirrus cloud demonstrated the ability for cloud dynamics study and for temperature measurement with modest aerosol or cloud contamination (backscatter ratio less than 5). These results have been included in a recent conference paper (Hair et al., 1997).

The updated performance of the Lidar can be seen in the profiles taken in the night of January 15, 1998. Between September, 1997, and January, 1998, we have developed a procedure for filter normalization without needing to open up the filter housing. This results in high filter stability during data acquisition. Hourly average temperature and backscatter ratio profiles are shown in Figure 9-4 in time sequence. In Figure 9-4a, the hourly temperature profiles are compared to a balloon sounding taken in Denver. A systematic bias (~ 10 K) is evident, but assuming reasonable variability that existed, the bias appears to be constant for all hours. The exact nature of this bias is still under study, although most likely due to insufficient spectral purity in the laser system at 532 nm, since the filters were monitored and found to be stable through the night. Field measurement and investigation in laser and iodine filters will continue to resolve this issue. Depending on the outcome of these investigations, the observed bias may be eliminated by either improving the laser spectral purity or introducing a re-normalization factor for data analysis.

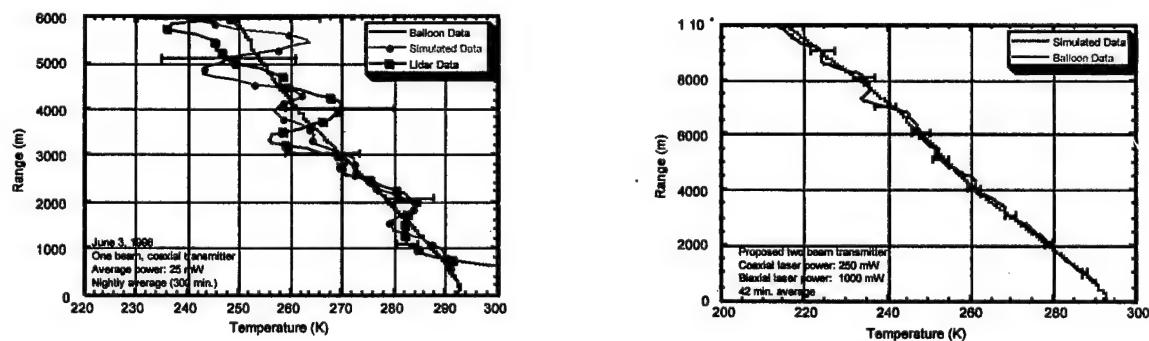


Figure 9-1. Left, Temperatures measured by Lidar and Balloon are compared to a simulated Lidar temperature profile based on the balloon temperatures as mean and added photon noise of the same signal level. Right, Simulated Lidar temperature profile with 250 mW coaxial and 1 W biaxial beams. Notice that much smaller errors are expected compared to Left.

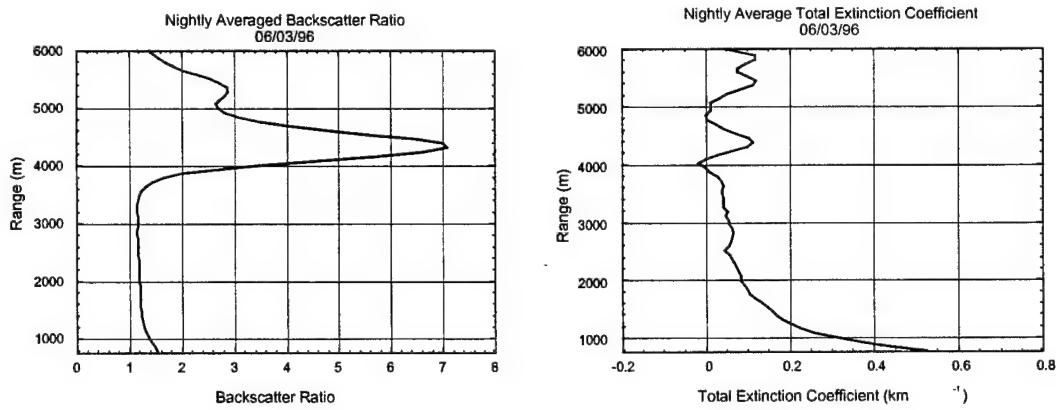


Figure 9-2. Simultaneously measured aerosol profiles at Fort Collins, CO on same night (June 3, 1996): Left, backscatter ratio and Right, total extinction profiles.

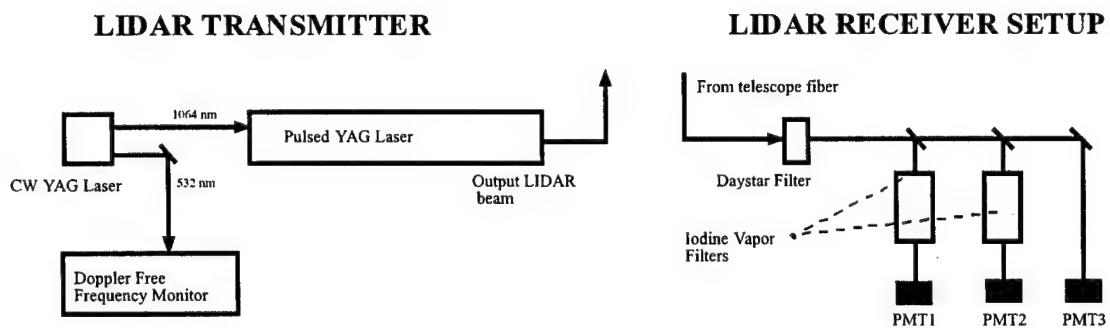


Figure 9-3. Schematic of HSRL transmitter and receiver. The transmitter system consists of the cw YAG laser to seed the pulsed YAG laser allowing a single longitudinal mode with 47 MHz linewidth. The receiver setup consists of the collected light being split into three channels, two with iodine filters measuring Rayleigh scattering only and one channel that measures the sum of Rayleigh and Mie scattering.

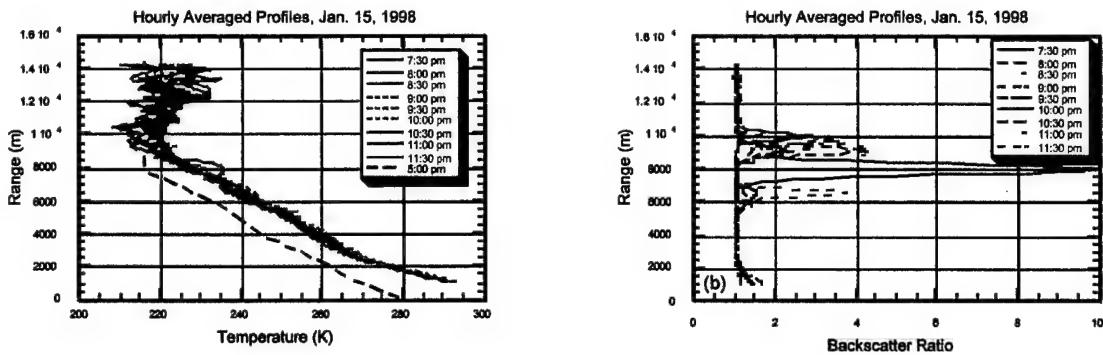


Figure 9-4. Observed hourly mean temperature (Left) and backscatter ratio (Right) profiles taken at Fort Collins, CO between 7:30 pm and 11:30 pm, Jan. 15, 1998, along with a Denver balloon sounding (bold dash line).

Technical Transition Activities

University Wisconsin and other LIDAR builders have begun incorporating the vapor filter technology invented with Geosciences funding.

Students Supported

John Hair, Physics - Ph.D. completed

Published Papers

Caldwell, L.M. J.W. Hair, D.A. Krueger, and C.Y. She, 1996: High spectral resolution Lidar using an iodine vapor filter at 589 nm. Presented at the SPIE Lidar Workshop, August, Denver, CO; published in Application of Lidar to Current Atmospheric Topics, Sedlacek Ed., SPIE Proceedings 2833, 40-45.

Hair, J.W., 1998: A high spectral resolution Lidar at 532 nm for simultaneous measurement of atmospheric state and aerosol profiles using iodine vapor filters. Ph.D. dissertation, Department of Physics, Colorado State University, Fort Collins, Colorado.

Hair, J.W. L.M. Caldwell, D.A. Krueger, and C.Y. She, 1996: A high spectral resolution Lidar for measuring aerosol extinction and atmospheric state parameters. 18th International Laser Radar Conference, July, Berlin, Germany.

Hair, J.W., L.M. Caldwell, D.A. Krueger, and C.Y. She, 1996: High spectral resolution Lidar for measuring aerosol and atmospheric state parameters using an iodine vapor filter at 532 nm. Presented at the SPIE Lidar Workshop, August, Denver, CO; published in Application of Lidar to Current Atmospheric Topics, Sedlacek Ed., SPIE Proceedings 2833, 241-250.

Hair, J.W., D.A. Krueger, and C.Y. She, 1997: High spectral resolution Lidar for measuring atmospheric state parameters and aerosol properties. Proceedings, 1997 Battlespace Atmospherics Conference, December 2-4, San Diego, CA.

Liu, Z.S., W.B. Chen, T.L. Zhang, J.W. Hair, and C.Y. She, 1996: An incoherent Doppler Lidar for ground-based atmospheric wind profiling. *Applied Physics*, (B)46, 561.

Liu, Z.S., W.B. Chen, J.W. Hair, and C.Y. She, 1996: Proposed ground-based incoherent Doppler Lidar with iodine filter discriminator for atmospheric wind profiling. In Application of Lidar to Current Atmospheric Topics, Sedlacek Ed., SPIE Proceedings 2833, 128-135.

Workshop Participation

July 16-18, 1997 DoD Center for Geosciences - Phase II Results Workshop
Pingree Park Mountain Campus, Colorado State University

July 29-31, 1998 Research Planning Retreat for the Center for Geosciences/Atmospheric Research, Pingree Park Mountain Campus, Colorado State University

Task 10: Measurement and Analysis of Complex Layered-Cloud Systems – Thomas H. Vonder Haar, Steve Cox, Graeme Stephens, John Davis, Don Reinke, John Forsythe, Stefan Tulich, Walt Petersen, Arlie Huffman

Original Intent (Goals) of the Research

It was recognized in the early 1990s – after Desert Storm and several peacekeeping activities – that the understanding and forecasting of mid-level cloud layers was an area for special research. Thus, the goals of this task were as follows: (a) investigate mid-tropospheric layered-cloud systems of special interest to DoD operations; (b) study the origin, duration and dissipation of mid-latitude and subtropical layer clouds; (c) develop new physical-based methods for detecting and estimating the extent of such clouds; (d) observe the radiative processes involved in their morphology and the effect on the neighboring environment; and (e) emphasize observations and methods closely related to new atmospheric numerical models used by DoD for research, simulation and operation.

Together these study goals could be framed in the following scientific questions:

- 1) Can cloud bases and layers be estimated using satellite-only techniques?
- 2) Can existing layer cloud conditions be detected and input into atmospheric models?
- 3) How does the cloud layer-induced radiative heating/cooling impact the layer cloud lifetime?

Research Findings and Results

New findings were obtained in each of the scientific question areas. In the course of investigating the first question, it was determined that present-day satellite systems have great difficulty in estimating cloud bases even when a combination of satellite infrared and microwave data were used (Olsen, 1996; Reinke et al., 1997). This negative result lead to two new research thrusts. The first approach developed a new way to combine satellite visible and infrared radiances with a bi-spectral cloud classification method and limited surface observations of cloud base. Given cloud conditions extending into hostile, data void areas it was found that cloud bases may be estimated with a 0.84 correlation to test results for mid-latitude continent conditions (Forsythe et al., 1999). The second portion of this line of inquiry on cloud bases lead us to support DoD needs by collaborating with NASA/JPL tests of an airborne 90 GHz cloud radar (Vonder Haar et al., 1997a, 1997b). Results were very promising and gave strong support to an early-1999 NASA/USAF/Canadian Space Agency decision to develop and launch (in 2003) the CloudSat Cloud Radar Mission for worldwide detection of cloud tops, bases and multiple cloud layers. CSU and JPL are the science and technical leaders of the CloudSat mission. The USAF Space Command will provide C³ and operation cloud detection tests are planned with DoD labs.

The global cloud data sets developed, in part, to aid this research were also used by USAF Capt. Tim Hall for two special cloud climatology studies. Hall (1997) and Hall and Vonder Haar (1999) provided new information on tropical cloud systems, of Navy interest, and Hall et al. (1997) provided new cloud information of Air Force and Navy interest over Yugoslavia (see the section on technical transfer, below).

The second science question above was addressed by a combined satellite and aircraft field experiment – the Complex Layered Cloud Experiment (CLEX). The principal cloud "targets" were long-lasting, spatially extensive layers on non-precipitating clouds located in the middle troposphere. Found in about 20-30% of cloud occurrences on a global basis, these clouds have until quite recently been relatively "forgotten" in cloud research. The advent of new DoD systems has required much more attention to the occurrence and forecasting of such clouds. Depending on season and location, these clouds in the +10 to -20 C range may be found from 0.75 to 3 KM ASL. The CLEX obtained both remote sensing and "in situ" cloud physics and environmental data for cloud layers over the central US (DoE ARM site) during Summer and over the tropical and mid-latitude Pacific during austral Spring. We were fortunate to obtain collaborations and data from JPL's cloud radar on NASA's DC-8 without special charge. Initial cloud analyses focused on detailed aircraft observations over limited area (Tulich, 1998; Vonder Haar et al., 1997a, 1997b).

The preliminary answer to science question 2 was positive since remote sensing could definitely distinguish certain cloud regions having distinct cloud ice and water mixtures (see also results from Neural Net studies in Task 13). Models of cloud systems carrying cloud water phase as explicit variables are being tested at both Navy and at European Centers in addition to those operating for research (e.g. CSU-RAMS). Convergence of research on such cloud layers is continuing within the DoD Center for Geosciences with a new USAF officer/graduate student, faculty and staff. Task 10 of the Center for Geosciences-Phase II began this line of inquiry which will lead forecasting for the DoD after several more years of dedicated cloud observations, diagnostic studies and forecast modeling.

Science question 3 above was addressed by both Olsen (1996) and Tulich (1998). Radiative heating and cooling processes are found to definitely be a contributing factor to cloud layer morphology. They cannot be neglected since their role is competitive with both advective and vertical motion processes. They will be given further study as the CLEX continues in the Fall of 1999.

Technical Transition Activities

As with several other Center for Geosciences research tasks, there will be continuing technical transfer of Task 10, Complex Layered-Cloud Systems, research in following the end of the ARO grant funding period. However, two specific transfers occurred. Following the Hall et al. (1996) paper on cloud conditions over Yugoslavia and the Adriatic at the Battlespace Atmospherics Conference, all these cloud climatologies were requested the AFWA planning

group in Europe. They were provided and an additional set of conditional cloud probability data were then developed (Hall et al., 1997) and provided at a later date.

Furthermore, the researchers and validation of 90 GHz cloud radar data mentioned in section above was provided to AFWA and USAF Space Command by Mr. Eis and Prof. Stephens of CSU. These results undoubtedly had influence on the Air Force decision to become a partner in the upcoming CloudSat Mission.

The USAF is interested in implementing a prototype cloud base spreading algorithm developed as part of this research theme. This technology transfer is expected to start before the end of 1999 and will be hosted on an AFWA computer.

Students Supported

Mark Botch, Atmospheric Science - Masters in progress

Timothy Hall, Atmospheric Science - Masters completed

Andy Heidinger, Atmospheric Science - Ph.D. completed

Arlie Huffman, Atmospheric Science - Ph.D. in progress

Lori Olsen, Atmospheric Science - Masters completed

Stefan Tulich, Atmospheric Science - Masters completed

Norm Wood, Atmospheric Science - Masters completed

Published Papers

Eis, K.E., J.M. Forsythe, and D.L. Reinke, 1996: The fractal behavior of cloud systems. Proceedings, 1996 Battlespace Atmospherics Conference, December 3-7, San Diego, CA.

Eis, K.E., J. Forsythe, and D. Reinke, 1997: The fractal behavior of cloud systems. Preprints, Cloud Impacts on DoD Operations and Systems, 1997 CIDOS Conference, September 23-25, Newport, RI.

Forsythe, J.M., D.L. Reinke, D.L. Randel, K.E. Eis, and C.L. Combs, 1996: CLVL: A global high-resolution layered-cloud database. Proceedings, 1996 Battlespace Atmospherics Conference, December 3-5, San Diego, CA.

Forsythe, J.M., T.H. Vonder Haar, and D.L. Reinke, 1999: Cloud base height estimates using a combination of meteorological satellite imagery and surface reports. *J. Appl. Meteor.* (submitted)

Hall, T.J., D.L. Reinke, and T.H. Vonder Haar, 1996: Forecasting applications of high resolution diurnal satellite cloud composite climatologies over former Yugoslavia and the Adriatic Sea. Proceedings, 1996 Battlespace Atmospherics Conference, December 3-7, San Diego, CA.

Hall, T.J., 1997: Diurnal cycle of deep tropical convection examined using high space and time resolution satellite data. Masters thesis, Spring Semester, Department of Atmospheric Science, Colorado State University, Fort Collins, CO.

Hall, T.J., and T.H. Vonder Haar, 1997: Diurnal cycle and morphology of deep tropical convection examined with a high resolution satellite data set. Preprints, 22nd Conference Hurricanes and Tropical Meteorology, May 19-23, Fort Collins, CO (AMS).

Hall, T.J., and T.H. Vonder Haar, 1997: Diurnal cycle of deep tropical convection examined using high space and time resolution satellite data. CIRA Report, ISSN #0737-5352, Colorado State University, Fort Collins, CO, September.

Hall, T.J., D.L. Reinke, and T.H. Vonder Haar, 1997: Forecasting applications of high resolution diurnal satellite cloud composite climatologies. *Wea. Forecasting*, 13(1), 16-23.

Hall, T.J., and T.H. Vonder Haar, 1999: The diurnal cycle of the West Pacific deep convection and its relation to the spatial and temporal variation of MCSs. *J. Atmos. Sci.* (accepted)

Miller, S.D., and G.L. Stephens, 1997: Multiple scattering effects in the Lidar pulse stretching problem. Department of Atmospheric Science Paper No. 642, Colorado State University, Fort Collins, CO, 156 pp.

Olsen, L. 1996: Analysis of infrared heating rates in observed cloud layers. Masters thesis, Department of Atmospheric Science, Colorado State University, 87 pp.

Reinke, D.L., J.M. Forsythe, and T.H. Vonder Haar, 1997: Global high-resolution layered cloud database - research and development at the Cooperative Institute for Research in the Atmosphere, Colorado State University. Preprints, Cloud Impacts on DoD Operations and Systems, 1997 CIDOS Conference, September 23-25, Newport, RI.

Tulich, S.N., 1998: Measured and calculated structures of a multi-layer altocumulus cloud. Masters thesis, Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado, 126 pp. (Available as Atmospheric Science Paper No. 647.)

Vonder Haar, T.H., S.K. Cox, G.L. Stephens, J.M. Davis, T.L. Schneider, W.A. Petersen, A.C. Huffman, K.E. Eis, D.L. Reinke, and J.M. Forsythe, 1997: Overview and Objectives of the DoD Center for Geosciences Sponsored "Complex Layered Cloud Experiment" (CLEX). Preprints, Cloud Impacts on DoD Operations and Systems, 1997 CIDOS Conference, September 23-25, Newport, RI.

Vonder Haar, T.H., S.K. Cox, G.L. Stephens, J.M. Davis, T.L. Schneider, W.A. Petersen, A.C. Huffman, K.E. Eis, D.L. Reinke, and J.M. Forsythe, 1997: Overview and Objectives of the DoD Center for Geosciences Sponsored "Complex Layered Cloud Experiment" (CLEX). Proceedings, 1997 Battlespace Atmospherics Conference, December 2-4, San Diego, CA.

Workshop Participation

January 19, 1995	Workshop on Two-Dimensional Surface Runoff Modeling Main Campus, Colorado State University Fort Collins, Colorado
July 16-18, 1997	DoD Center for Geosciences - Phase II Results Workshop Pingree Park Mountain Campus, Colorado State University
July 29-31, 1998	Research Planning Retreat for the Center for Geosciences/Atmospheric Research, Pingree Park Mountain Campus, Colorado State University

Task 11: NEXRAD/CSU-CHILL Algorithm Studies – V. Bringi, V. Chandrasekar

Original Intent (Goals) of the Research

This theme's goals were three-fold:

1. Conduct basic and applied research to understand the limitations of the hail detection algorithm used by NEXRAD by comparing the CSU-CHILL data directly with the WSR-88D hail products.
2. Conduct research designed to understand the limitations of the precipitation analysis products, specifically, as related to contamination of rainfall estimates by frozen precipitation such as hail, snow, bright-band, freezing rain, etc.
3. Lastly, the DOD panel was most interested in any developed algorithms being validated with observational data.

Research Findings and Results

1. Field research in support of this theme was highly successful with several large hail events fully documented. Ground validation included coop hail and rain gauge readings around the CHILL sensing area, and fully instrumented hail collection vans collecting hail rate, and size information as well as wind and rain rate information (see Figure 11-1a,b, and c).

Additionally, an armored T-28 storm penetrating aircraft carrying a two dimensional hail probe (HVPS) (see Figure 11-2) penetrated several storms being painted by the CHILL radar and in conjunction with the ground-based observer and data collection systems. Figure 11-3 shows the hail images collected by the HVPS. Both the vans and the T-28 benefited from the newest hail sensor technology that allowed CSU researchers to measure hail size and habit as well as fall rates and 3-dimensional velocities with unprecedented accuracy.

2. One example of the full 3-dimensional representation of a supercell was collected on 7 June 1995. Figure 11-4 shows the graphical representation of the data collection from CHILL. The analysis of this cell, in conjunction with in situ data collection gave new insights into the ZDR column's importance as the basis of hail and rain rate algorithms.
3. Table 11-1 gives a summary of the most significant data collection events taken during the field program.
4. The ZDR relationship, used by NEXRAD, in the presence of hail, was shown to be approximately 50 percent off. This is a most significant finding since most flash flood events are due to thunderstorms where hail is present. This finding also points to the need for dual

polarization capability in the future replacement for the WSR-88D. Only dual polarization processing can distinguish hail and rain which need to be separated for the proper calibration of both returns.

5. An error minimization scheme was developed to optimally map radar based rain rate to surface measurements. The success of this algorithm was extended to produce a new radar based algorithm to obtain improved surface rainfall estimates.
6. The hail threshold used by NEXRAD was evaluated and was shown to be a function of the storm and season.



Figure 11-1a. "Hailstone" van showing the NCAR hail catcher net.



Figure 11-1b. 2-D Video Distrometer mounted on "Austria" van.

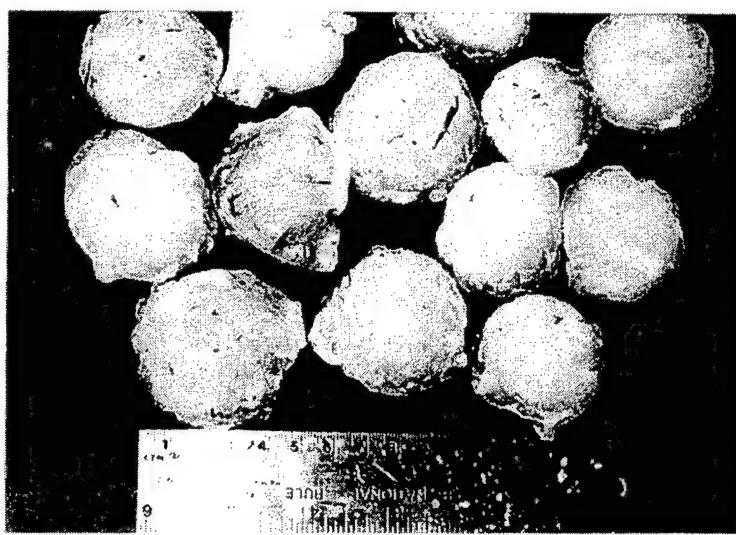


Figure 11-1c. Sample of "Golf Ball" hailstones from 7 June 1995 storm.

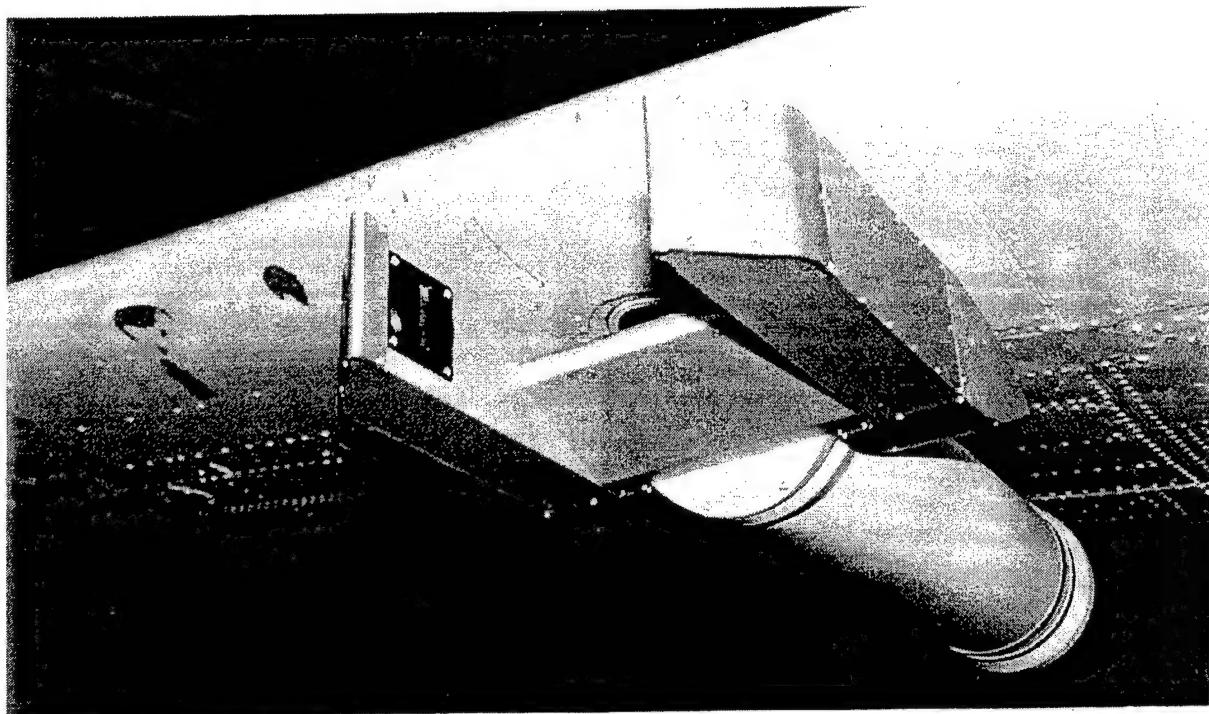


Figure 11-2. High Volume Particle Spectrometer (HVPS) mounted on the T-28 aircraft.

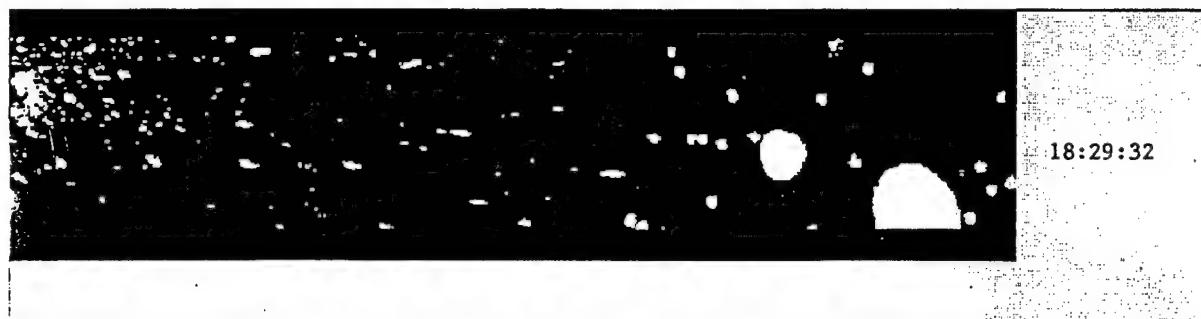


Figure 11-3. Sample image from High Volume Particle Spectrometer (HVPS) flown on the T-28 aircraft.

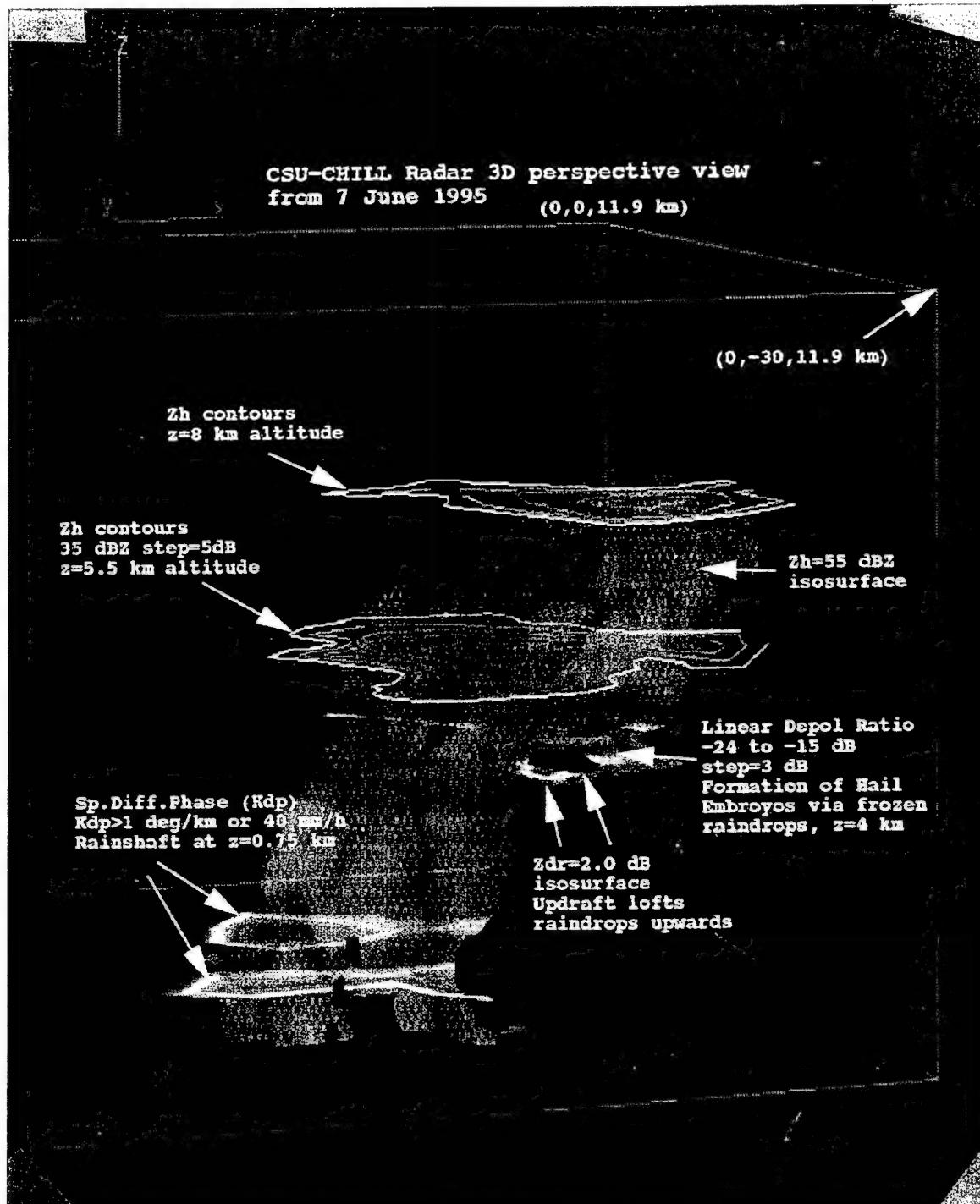


Figure 11-4

Table 11-1. Summary of HVPS, 2D-Video and Hailstone Van Events

a. T-28/HVPS Datasets (see Detweiler et al. 1996)

20 June, 1995 (Operations from 1600 - 1714 MDT)

There were 13 penetrations, most of them $\sim -8.5^{\circ}\text{C}$, in thunderstorm cells at range of ~ 35 km from CSU-CHILL radar. Predominant precipitation was low-density graupel (see Fig. 10).

22 June, 1995 (1712 - 1806)

There were 4 penetrations in a hailstorm and the T-28 encountered large hail (up to 2 cm diameter) on several passes (see Fig.7). There was significant damage to the 'un-armored' surfaces of the airframe and to the cooling fins on 3 cylinders.

27 June, 1995 (1510 -1630)

There were 15 penetrations at -2 to -8°C with soft hail that was generally pea-to-marble size, but occasionally up to ping-pong ball size.

28 June, 1995 (1758 - 1940)

There were 10 penetrations through a large area of stratiform precipitation at +6 to -8°C . Large particles were recorded at and below the bright-band.

b. 2D-Video Disdrometer (Summer Events)

21 June, 1995

Convective rain event lasting for ~ 15 minutes at close range (~ 30 km) documenting dsd transition as shown in Fig.4 (see, also, Hubbert et al. 1997b).

8 August, 1995

Convective cell with large raindrops (up to 7 mm diameter) was sampled at very low rain rates with high Zdr (up to 4 dB) and low Kdp ($\sim 1^{\circ}\text{km}^{-1}$), see Fig. 18.

10 June, 1996

Convective cell sampled for 16 minutes with large drops (up to 7 mm) and tiny, melting hail. Peak rain rates up to 35 mmh^{-1} . Flat-tailed dsd from 3 - 7 mm.

14 June, 1996

Convective cell sampled for 13 minutes with large drops (up to 7 mm) and peak rain rates up to 65 mmh^{-1} . Non-gamma dsd with excess of big drops (relative to MP) in the range 3 - 6 mm. Weak horizontal winds.

15 June, 1996

25 minute light rain event (stratiform) with $R < 1 \text{ mmh}^{-1}$ and maximum diameter of 2.5 mm. Nice exponential distribution.

20 June, 1996

First event was 9 minutes with peak R of 45 mmh^{-1} with no hail. Fairly exponential shape with max D of 6 mm.

The second event was 10 minutes with peak R of 100 mmh^{-1} with sparse pea-sized hail. However, max. drop diameters around 5 mm and nearly exponential-shaped dsd.

21 June, 1996

Twelve minute event with peak R of 15 mmh^{-1} . Max. drop diameter of 5 mm. Nearly exponential dsd for D from 1 - 5 mm.

Table 11-1 (Continued)

24 June, 1996

First event was nine minutes with all ice hydrometeors (D up to 6 mm). No drops were observed.

Flat dsd from 1 - 6 mm.

Second event was 15 minutes long with light rain rates but flat-tailed dsd from 3 - 7 mm.

Third event was 50 minutes long with significant hail in the first twenty minutes (peak hail rates of 30 mmh^{-1} and sizes up to 14 mm).

28 June, 1996

Nine minute rain event with moderate rates with exponential dsd from 1 - 5 mm, and flat-tailed from 5 - 8 mm.

6 July, 1996

Twenty minute event in a squall-line type storm with rain and pea-to-marble sized hailstones.

Peak rain rates up to 90 mmh^{-1} , drop sizes up to 8 mm. Concave-shaped dsd. System outages caused by high rates for around two minutes.

9 July, 1996

Twenty five minute rain event with peak $R \sim 40 \text{ mmh}^{-1}$ and drops up to 6 mm. Nice exponential dsd from 0.5 - 4 mm. Coordinated with S-POL radar primarily on this day.

13 July, 1996

Twenty minute event of rain mixed with hail up to marble-sized. Peak $R \sim 60 \text{ mmh}^{-1}$.

24 July, 1996

Fourteen minute event with very little rain, and dominated by pea-to-marble sized hail. Flat-tailed dsd from 3 - 7 mm. Max. hail sizes ~ 12 mm were detected.

26 July, 1996

Two events, the first was 12 minutes long of rain mixed with pea-to-marble hail. Second event was 9 minutes with heavy rain only.

29 July, 1996

Light stratiform rain for 90 minutes with $R < 5 \text{ mmh}^{-1}$.

2 May, 1997

2D-video van deployed to Wichita, Kansas (CASES project) for collection of data with S-POL radar. One squall-line event was sampled for an hour with distinct convective-to-stratiform transition. Brief convective pulse with peak R of 30 mmh^{-1} ; long stratiform period with $R < 10 \text{ mmh}^{-1}$. Max. drops of up to 4.5 mm. Well documented dsd changes throughout event.

c. Hailstone Van Events

7 June, 1995

Severe hailstorm with golfball hail (see Fig. 14, 15). Event sampled for ~ 45 minutes. Rainfall accumulation was 40 mm.

22 June, 1995

Hailstone van made two intercepts. The first one was same storm as the T-28 sampled except a little later (~ 15 minutes). Sparse golf ball hail was collected. The second event was another hailstorm with marble-sized hail.

Table 11-1 (Continued)

6 July, 1996

Rain and hail data collected for a period of 30 minutes as cell passed overhead (25 mm total accumulation). Peak rain rates exceeded 100mm/hour. Mixed with marble size hail up to 17 mm.

9 July, 1996

Steady moderate rainfall collected for 30 minutes. The total accumulation was 10 mm, with a peak rain rate of 50 mm/hour. Coordinated with S-POL radar.

12 July, 1996

Light rain mixed with hail. Large marble size hail was collected for 4 minutes in the hail net, also some hand collected on the ground around the van. Total rain accumulation was 10 mm over a period of 25 minutes.

26 July, 1996

Intercept a cell with mixed rain and hail. Rain lasted for 20 minutes with a total of 30 mm of accumulation and peak rain rates of over 100 mm/hour. Pea-to-large marble size hail was collected.

28 July, 1996

Very good hail intercept. Collected 12 bags of hail. Collection lasted for 7 minutes and some hailstones were hand collected off the ground after the event. Sizes were up to golf ball. Total rain accumulation was 20 mm, with peak rates exceeding 150 mm/hour.

31 July, 1996

Very large storm passed over northern Colorado. Van collected baseball size hail off of the ground. Ground dense with golf ball size and larger hailstones. Hailswath was followed by the van giving latitude/longitude of large hail fall locations.

Technical Transition Activities

Algorithm information given to the NEXRAD science working group.

Students Supported

John Beaver, Electrical Engineering

G. Huang, Electrical Engineering - Masters completed

Matt Taggart, Electrical Engineering

Published Papers

Abou-El-Magd, A.M., V. Chandrasekar, and V.N. Bringi, 1997: Simultaneous radar and in-situ aircraft based observations of convective storms: Intercomparison study. Proceedings, IEEE Geoscience and Remote Sensing Symposium, August 3-8, Singapore, pp. 1457-1459.

Bolen, S., V.N. Bringi, and V. Chandrasekar, 1996: An optimal area approach to intercomparing polarimetric radar rain rate algorithms with gauge data. *J. Atmos. Ocean Tech.*, 15(3), 605-623.

Bolen, S., V.N. Bringi, and V. Chandrasekar, 1997: An assessment of multiparameter radar rain rate algorithm using optimal area approach. Proceedings, IEEE Geoscience and Remote Sensing Symposium, August 3-8, Singapore.

Bolen, S., V.N. Bringi, and V. Chandrasekar, 1997: A new approach to compare polarimetric radar data to surface measurements. Preprints, 28th Conference on Radar Meteorology, Sept 7-12, Austin, TX.

Bolen, S., V.N. Bringi, and V. Chandrasekar, 1998: An optimal area approach to intercomparing polarimetric radar rain rate algorithms with gauge data. *J. Atmos. Ocean. Tech.*, 15, 605-623.

Bringi, V.N., and V. Chandrasekar, 1997: The CSU-CHILL fully polarimetric S-band weather radar facility: Providing research experience of undergraduates. Proceedings, IEEE Geoscience and Remote Sensing Symposium, August 3-8, Singapore.

Huang, G., V.N. Bringi, and J. Beaver, 1997: Application of the polarization power matrix in analysis of convective storm data using the CSU-CHILL radar. Preprints, 28th Conference on Radar Meteorology, Sept 7-12, Austin, TX (AMS).

Hubbert, J., V.N. Bringi, L.D. Carey, and S. Bolen, 1998: CSU-CHILL polarimetric radar measurements from a severe hail storm in Eastern Colorado. *J. Appl. Meteor.*, 37(8), 749-775.

Hubbert, J., V.N. Bringi, V. Chandrasekar, M. Shonhuber, H.E. Urban, and W.L. Randeu, 1997: Storm cell intercepts using a mobile 2D-video distrometer in conjunction with the CSU-CHILL radar. Preprints, 28th Conference on Radar Meteorology, Sept 7-12, Austin, TX (AMS).

Workshop Participation

January 19, 1995	Workshop on Two-Dimensional Surface Runoff Modeling Main Campus, Colorado State University Fort Collins, Colorado
July 16-18, 1997	DoD Center for Geosciences - Phase II Results Workshop Pingree Park Mountain Campus, Colorado State University
July 29-31, 1998	Research Planning Retreat for the Center for Geosciences/Atmospheric Research, Pingree Park Mountain Campus, Colorado State University

**Task 13: Neural Network Approach to Cloud Data Analysis – Mahmood R. Azimi-Sadjadi,
Bin Tian, Mukhtiar Shaikh, Don Reinke**

Original Intent (Goals) of the Research

The purpose of this research task was to extend the normal textural analysis of clouds beyond that of the conventional neural network analysis of the past. Proposed work included detailed analysis of feature extraction schemes, the use of all satellite visible and IR channels in the neural network analysis, and the development of an optimized neural network structure for cloud classification. The neural network system is depicted in Figure 13-1. The optimization of a neural network process includes the judicious selection of a Feature Extractor, and only then the selection of an appropriate neural network classifier. Another critical part of the process is the development of a training set where clouds have been classified independently.

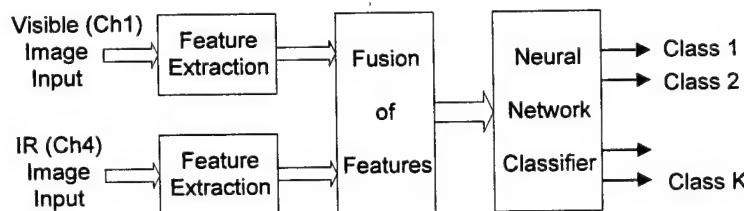


Figure 13-1. The block diagram of the cloud classification system.

Research Findings and Results

Feature Extraction – Before the GOES cloud images were provided to the Neural Network classifier the images were first sent to a feature extraction engine. The candidate feature extraction methods that were tested and compared were: Singular Value Decomposition (SVD) Wavelet Transform (WT), Gray Level Co-occurrence Matrices (GLCM), and the Gabor Transform (GT). These feature extractors are used to both compress the informational content of the GOES IR and visible images, and to extract the cloud features from them. Data extracted included textural, intensity, and shape-dependent features in the satellite, multi-spectral images. Output statistics from the extraction engines included mean, standard deviation, contrast, correlation, entropy, and homogeneity. The image area tested is depicted in Figure 13-2. Note that the analysis area covers all of the US to the Rocky Mountains and a good part of SE Canada, Northern Mexico and the Caribbean. Results of the analysis indicated that the WT feature extractor gave the best results.



Figure 13-2. Original GOES 8 IR Image (Time 16:45 UTC, May 1, 1995).

Neural Network (NN) Selection – Several neural network topologies were tested against the test set developed by the CIRA staff. These networks included Probability Neural Network (PNN), and the Kohonen Self Organized Map (SOM) networks. Note that the PNN is a supervised (forced set of output classifications), and the Kohonen is an unsupervised network. (clusters or classes are identified by the system itself). The popular Maximum Likelihood (ML) classification scheme was also used for comparison purposes.

Simulations were run with various combinations of Feature Extractors and NNs. The classifiers that were identified in the training set included the following classes: Warm Land (WLnd), Cold Land (CLnd), Warm Water (WWtr), Cold Water (CWtr), Cumulus (Cu), Altostratus (CS), Stratocumulus(SC), Cirrus Over Land (CiOL), Cirrus Over Water (CiOW) and CirroStratus (Cs). Figure 13-3 depicts a typical test data set used to train the NN. Figure 13-4 depicts the PNN (using WT) classification of one of the images. Figure 13-5 shows the statistics for the image when compared with test data sets, independent of the training sets. Note that the SOM1,2, and 3 depict Kohonen Self Organized Map (SOM) with 10,20, and 30 output neurons.

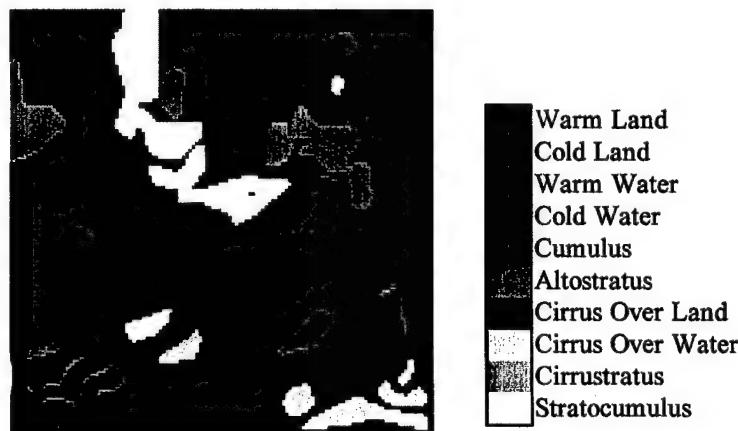


Figure 13-3. Cloud /background classes labeled by the experts.

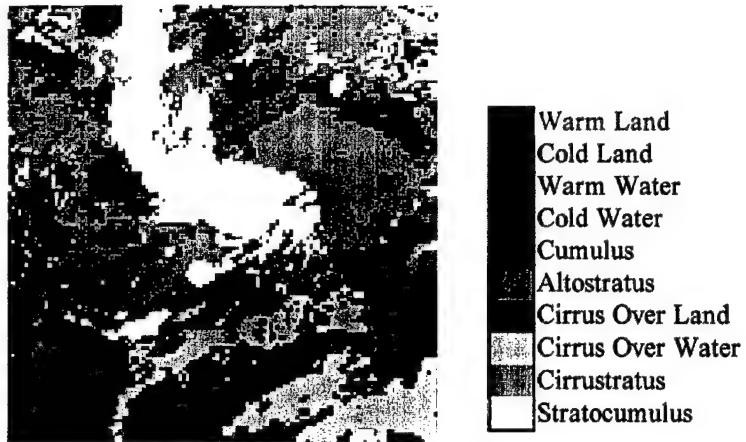


Figure 13-4. PNN Processed Image (WT).

	WLnd	CLnd	WWtr	CWtr	Cu	As	CiOL	CiOW	Cs	Sc	Class Avg. Accuracy	Overall Accuracy
SOM1	1.00	0.88	1.00	0.00	0.68	0.22	0.62	0.00	0.99	0.76	0.62	0.64
SOM2	1.00	0.27	1.00	0.00	0.98	0.45	0.76	0.91	0.93	0.98	0.73	0.82
SOM3	0.99	0.65	0.96	0.00	0.97	0.72	0.71	0.84	0.97	0.90	0.77	0.82
ML	0.98	1.00	0.95	1.00	0.98	0.41	0.77	0.91	0.93	0.88	0.88	0.80
PNN	1.00	1.00	0.99	1.00	1.00	0.77	0.72	0.98	0.98	0.95	0.94	0.86

Figure 13-5. Classification accuracy for different kinds of classifiers using WT features.

Creation of a novel temporal updating scheme for the PNN – All of the neural network classification schemes suffer from a drift in class definitions as solar illumination and IR surface heating develop during the day. This problem was overcome when the researcher (Bin Tian) developed a temporal updating scheme that gradually redefined the class definitions as the scene changed during the day (see Bin Tian's dissertation for details of this method). The result of this updated PNN was an improved classification (approximately 10 percent) over the static PNN statistics.

Technical Transition Activities

Fine-tune the layered cloud analysis model that uses a simple bi-spectral technique, or a more robust neural network technique. This analysis model has been tested on a limited number of cases and shown to have a great potential for improving on current objective analysis techniques.

Temporal updating scheme being considered as candidate transition to AFWA via Aerospace Corp. Additionally the temporal updating is being considered for CSU licensing and copyright.

Students Supported

Bin Tian, Electrical Engineering - Ph.D. in progress

Mukhtiar Shaikh, Electrical Engineering - Masters completed

Published Papers

Azimi-Sadjadi, M.R., M.A. Shaikh., B. Tian, K.E. Eis, and D. Reinke, 1996: Neural network-based cloud detection/classification using textural and spectral features. Proceedings, 1996 International Geoscience and Remote Sensing Symposium, Lincoln, NE, IEEE, p. 1105-1107.

Shaikh, M.A., 1996: Neural network-based cloud detection/classification using various textural feature extraction schemes. Masters thesis, Department of Electrical Engineering, Colorado State University, 125 pp.

Shaikh, M.A., B. Tian, M.R. Azimi-Sadjadi, K.E. Eis, and T.H. Vonder Haar, 1996: An automatic neural network-based cloud detection/classification scheme using multispectral and textural features. Proceedings, SPIE'96 Conference, April, Orlando, FL, Society of Photo-Optical Instrumentation Engineers.

Tian, B., M R. Azimi-Sadjadi, N.A. Shaikh, and T.H. Vonder Haar, 1996: An FFT-based algorithm for computation of gabor transform with its application to cloud detection/classification. Proceedings, 1996 International Geoscience and Remote Sensing Symposium, Lincoln, NE, IEEE, p. 1108-1110.

Tian, B., M.R. Azimi-Sadjadi, T.H. Vonder Haar, and D.L. Reinke, 1997: Neural network-based cloud classification using textural features. IEEE International Conference on Image Processing'97, vol.3, 209-212, Oct 26-29, Santa Barbara, CA.

Tian, B., M.R. Azimi-Sadjadi, K. Eis, and T.H. Vonder Haar, 1997: A novel temporal updating scheme for cloud classification. Proceedings, 1997 Battlespace Atmospherics Conference, December 2-4, San Diego, CA.

Tian, B., M.R. Azimi-Sadjadi, T.H. Vonder Haar, and D.L. Reinke, 1998: A temporal adaptive probability neural network for cloud classification from satellite imagery. IEEE Transactions on Neural Networks 1998 (in press).

Tian, B., M.R. Azimi-Sadjadi, T.H. Vonder Haar, and D.L. Reinke, 1997: Temporal updating scheme for probability neural network with application to satellite cloud classification. IEEE Transactions on Neural Networks 1998 (in press).

Tian, B., M.A. Shaikh, M.R. Azimi-Sadjadi, T.H. Vonder Haar, and D.L. Reinke, 1997: Neural network-based cloud classification using textural features. IEEE Transactions on Neural Networks 1998 (submitted).

Workshop Participation

January 19, 1995	Workshop on Two-Dimensional Surface Runoff Modeling Main Campus, Colorado State University Fort Collins, Colorado
July 16-18, 1997	DoD Center for Geosciences - Phase II Results Workshop Pingree Park Mountain Campus, Colorado State University
July 29-31, 1998	Research Planning Retreat for the Center for Geosciences/Atmospheric Research, Pingree Park Mountain Campus, Colorado State University

Task 15: Atmospheric Compression Waves – Roger Pielke, Melville Nicholls, Alfred Bedard

Original Intent (Goals) of the Research

The goal of this task was to try and detect thermal compression waves generated by heat release in thunderstorms using acoustic arrays. This has the potential of providing the military a passive sensor for locating thunderstorm development areas. Previous works by Nicholls and Pielke (1994a and b) have used idealized numerical simulations to demonstrate the existence of this type of compression wave. In order to determine the amplitude, shape and decay rate of thermal compression waves likely to be generated by actual thunderstorms, the intent was to modify the Colorado State University Regional Atmospheric Modeling System (CSU-RAMS) so as to provide more realistic fully compressible three-dimensional simulations of thunderstorms and the compression waves generated. These results were to provide guidelines for the required resolution of acoustic sensors and their deployment in the field. Acoustic sampling networks were to be deployed during periods of convective activity and this deployment coordinated with radar observations at the CHILL radar site in northeastern Colorado. The first objective of the observational program was to see if thermal compression waves could be identified in the pressure time series. If successful, then data analysis using three acoustic sensors would be carried out to attempt to determine the direction a thermal compression wave came from.

Research Findings and Results

The CSU-RAMS model was successfully modified to be fully compressible and simulations were carried out of both isolated and multiple convective storms. In order to realistically simulate the thermal compression waves, multiple nested grids were required to provide good resolution of the convective storms and a very large domain size, in excess of 2000 km in width. Additionally, the height of the model domain needed to be set at the high level of 80 km in order to provide for a deep upper level absorption layer which prevents acoustic waves reflecting downwards and enabling the accurate simulations of surface pressure perturbations. The amplitude of the surface pressure perturbations produced by thermal compression waves was between 1-2 Pa at a distance of 100 km from isolated thunderstorms. In addition to the numerical simulations, an idealized theoretical model of thermal compression waves was developed. This model showed that these waves should decay inversely with the square root of distance travelled from the source and the numerical model simulations confirmed this result. Additionally, analysis of the vertical structure of the numerically-simulated compression waves firmly established that they are Lamb waves. These are compression waves which are hydrostatically balanced in the vertical and propagate in the horizontal plane at the speed of sound. The theoretical and numerical models also provided useful information concerning the shape the waves would have in pressure time series recorded at the surface some distance from the storm.

In the summer of 1995 three acoustic sensors were deployed. One was stationed at the CHILL radar site and the others in mobile units which could be positioned close to thunderstorms. The data clearly showed examples of large amplitude, slow moving, thermally-

induced gravity waves which were predicted by the numerical simulations. It became evident that the smaller amplitude compression waves were not going to be detectable with the current pressure sensor. Effort focused on the design of a new pressure sensor with a significantly improved ability to resolve small amplitude low frequency signals. This new sensor was tested in the field during the summer of 1997. In light of the experience with the previous field study, it was decided the best way to establish the existence of thermal compression waves would be to deploy three sensors placed approximately 10 km apart. This close deployment, while not large enough to determine the precise phase speed and propagation direction of thermal compression waves, does permit us to distinguish them from gravity waves. The fast moving thermal compression waves will appear across the array essentially simultaneously since it takes only 30 s for them to propagate 10 km. On the other hand, the fastest moving gravity wave modes take approximately 300 s. On 27 August 1997, a strong candidate for thermal compression waves was detected at the array. The simultaneous pressure rise at all three sites appeared to be caused by compression waves emanating from a number of convective cells that had developed at the same time.

This research has made considerable progress in understanding the properties of thermal compression waves generated by thunderstorms and has possibly provided the first example of their detection. It is clear that there still needs to be improvements to the resolution of the pressure sensor. The first step for future research would be to use an improved pressure sensor in a closely spaced array to provide conclusive evidence that thermal compression waves can be detected. If this were accomplished, then multiple sensor arrays could be deployed to establish the direction and distance of the source. Given that observations are likely to be made in situations when large amplitude gravity waves are present, then signal processing techniques would be required to extract the components of the signal due to the faster moving compression waves. Ultimately, the desired product one would like to achieve would be a map of convective activity and its time evolution. This problem is similar to those addressed by inversion techniques often encountered in remote sensing and tracer transport problems, where you want to determine the sources of a tracer given measurements of concentration at a few locations. It is possible that the numerical model, or a much more computationally efficient theoretical model, could be used in an analogous way to a transport model in a tracer transport problem.

References

Nicholls, M.E., and R.A. Pielke, 1994a: Thermal compression waves. I: Total energy transfer. *Q.J.R. Meteorol. Soc.*, 120, 305-332.

Nicholls, M.E., and R.A. Pielke, 1994b: Thermal compression waves. II: Mass adjustment and vertical transfer of total energy. *Q.J.R. Meteorol. Soc.*, 120, 333-359.

Students Supported

Joseph Eastman, Atmospheric Science - Ph.D. in progress

Published Papers

Nicholls, M.E., and R.A. Pielke, 1995: A numerical investigation of the effect of vertical wind shear on tropical cyclone intensification. Proceedings, 21st Conference on Hurricanes and Tropical Meteorology, April 24-28, Miami, FL, 339-341 (AMS).

Nicholls, M.E., and R.A. Pielke, 1998: Thermally-induced compression waves and gravity waves generated by convective storms. *J. Atmos. Sci.* (accepted).

Pielke, R., M.E. Nicholls, T.A. Nygaard, and R.L. Walko, 1997: Several unresolved issues in numerical modeling of geophysical flows. In: Numerical Methods in Atmospheric and Oceanic Modelling, The Andre J. Robert Memorial Volume, C.A. Lin, R. Laprise, and H. Ritchie, Eds., 557-581.

Workshop Participation

January 19, 1995 Workshop on Two-Dimensional Surface Runoff Modeling
 Main Campus, Colorado State University
 Fort Collins, Colorado

May 16, 1996 Atmospheric Compression Waves (Task 15) Working Group Meeting
 CIRA, Foothills Campus, Colorado State University
 Fort Collins, Colorado

July 16-18, 1997 DoD Center for Geosciences - Phase II Results Workshop
 Pingree Park Mountain Campus, Colorado State University

July 29-31, 1998 Research Planning Retreat for the Center for Geosciences/Atmospheric Research, Pingree Park Mountain Campus, Colorado State University

Research Support

In all large, multi-disciplinary research activities there are a number of infrastructure-type developments which support all tasks. The papers and publications listed below provide an indication of the many activities at Colorado State University that supported the DoD Center for Geosciences-Phase II.

Published Papers

Dean, K., K. Eis, and T.H. Vonder Haar, 1996: GVAR image application in interactive data language. Preprints, 12th International Conference on Interactive Information Processing Systems for Meteorology, Oceanography, and Hydrology, Jan 28 - Feb 2, Atlanta, GA (AMS).

Hiatt, M., 1996: A GOES, AVHRR, and METEOSAT frame synchronizer design implemented in a single Xilinx FPGA. Preprints, 12th International Conference on Interactive Information Processing Systems for Meteorology, Oceanography, and Hydrology, Jan 28 - Feb 2, Atlanta, GA (AMS).

McClurg, N., D. Reinke, and M. Hiatt, 1996: Low maintenance PC-based 30 GB GOES-8 data access and archive system. Preprints, 12th International Conference on Interactive Information Processing Systems for Meteorology, Oceanography, and Hydrology, Jan 28 - Feb 2, Atlanta, GA (AMS).

Reinke, D.G., J.F.W. Purdom, and T.H. Vonder Haar, 1996: Navigation of NOAA Level II NEXRAD data for alignment with MCIDAS GOES satellite imagery. Preprints, 12th International Conference on Interactive Information Processing Systems for Meteorology, Oceanography, and Hydrology, Jan 28 - Feb 2, Atlanta, GA (AMS).

Whitcomb, D., R. Gartner, K. Eis, and T.H. Vonder Haar, 1996: GOES I-M data collection software and algorithms. Preprints, 12th International Conference on Interactive Information Processing Systems for Meteorology, Oceanography, and Hydrology, Jan 28 - Feb 2, Atlanta, GA (AMS).

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